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Crop residue management and tillage methods for conserving soil and water in semi-arid regions

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ABSTRACT

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Soil degradation reduces soil productivity and is a serious problem on much of the land in semi-arid regions. To avert continued degradation, the soil productivity balance must be shifted from degrading processes to conservation practices. Crop residue management and conservation tillage are on the positive side of the balance. When adequate residues are available and conservation tillage is used, soil erosion is greatly reduced and water conservation is enhanced. Water conservation is important for improving crop yields in semi-arid regions, especially where irrigation is not used. A major constraint to residue management in many countries is low production and widespread use for other purposes. In such cases, clean tillage and appropriate support practices such as contouring, furrow diking, strip cropping and terracing may provide adequate soil and water conservation benefits. Where these are not adequate, alternative management practices should be implemented to ease the demand for residues, thus permitting more of them to be retained on the land for soil and water conservation purposes. Some alternative practices include limited or selective residue removal, substituting high quality forages for residues as animal feed, alley cropping, using wasteland areas more effectively, improving the balance between feed supplies and animal populations, and using alternative fuel sources.

INTRODUCTION

Low and erratic precipitation is the single most important climatic factor that limits crop yields in most semi-arid regions (Lal, 1990). Soil factors, including texture and profile depth, which affect water storage capacity, pH, fertility and salinity, also have a major impact on yields. If soil factors are not in balance with the prevailing precipitation, crop yields will be below their potential. In addition, soil productivity may be impaired because degradation processes outweigh the conservation practices (Fig. 1).

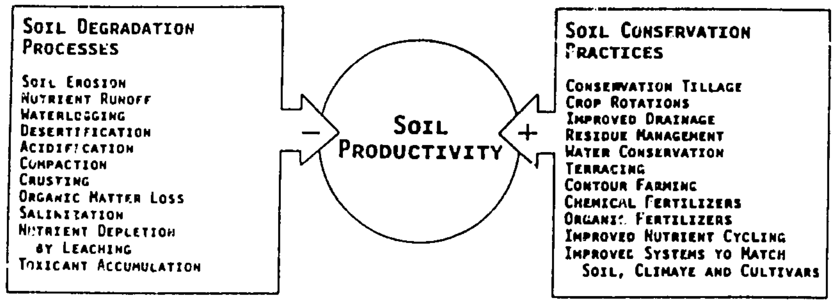

Fig. 1. Relationship of soil productivity to soil degradative processes and soil conservation practices (from Stewart et al., 1991).

To avert continued degradation, conservation practices that positively influence productivity (Fig. 1) must be implemented. Two practices having a major impact on soil conservation are crop residue management and tillage. Although these practices are emphasized in this report, other related practices will be mentioned, where appropriate. Also, it is assumed that undesirable soil conditions that may interfere with conservation efforts related to residue management and tillage have been corrected.

The severity of some factors that negatively affect soil productivity are shown for selected soil orders in Fig. 2. The dominant soils in semi-arid regions are the Aridisols, followed by Alfisols, Mollisols, Oxisols and Vertisols. Ultisols generally do not occur in semi-arid regions.

Most Aridisols occur in warm to hot and dry regions where the difficulty of achieving production sustainability is greatest (Fig. 3). The generalized relationships (Fig. 3) integrate the effects of temperature and precipitation, and show that as temperature increases and precipitation decreases, the development of sustainable cropping systems becomes more difficult. The relationships do not apply to all climatic regions. Certainly, sustainability of production may become more difficult under very high precipitation regimes owing to erosion, nutrient leaching and acidification. Under cold conditions, the choice of cropping systems may be limited and soil water logging may occur (Stewart et al., 1991). Also, where precipitation is more reliable, production may be more sustainable than where precipitation is more variable, even though mean precipitation may be greater in the latter case.

Reasons for the temperature and precipitation effects (Fig. 3) are obvious when the processes and practices illustrated in Fig. 1 are analyzed. In many cases, the most dominant soil-degrading processes are erosion and organic matter decline. As temperatures increase, soil organic matter decline is accelerated, especially where tillage is frequent. The potential for erosion, especially by wind, also generally increases in warm regions. Organic matter decline and erosion are further accelerated as the climate becomes drier because

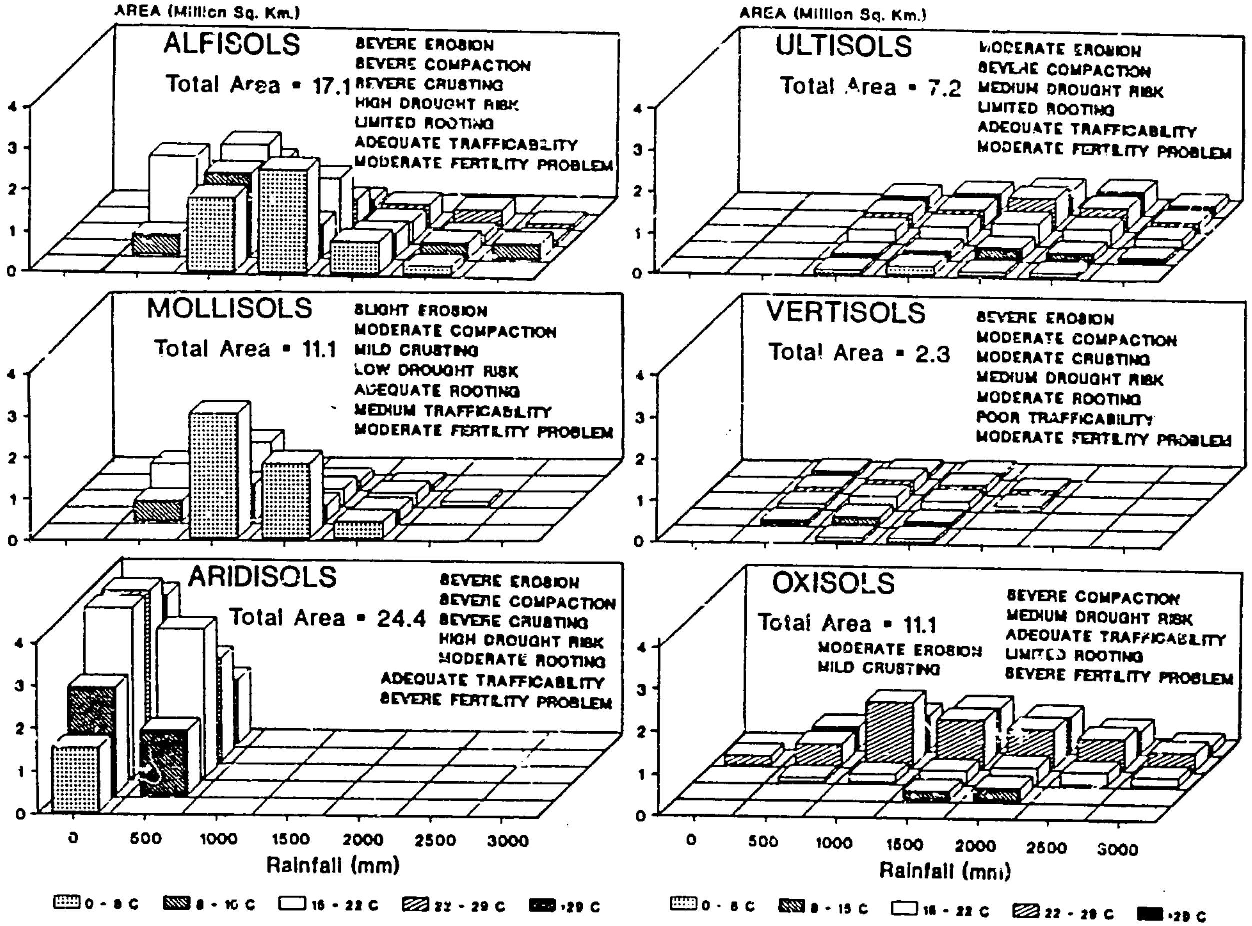

Fig. 2. Approximate climatic distribution, area and chief constraints of selected soil orders (from Stewart et al., 1990).

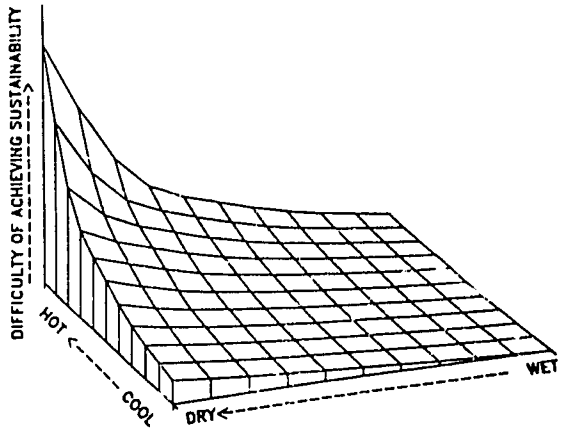

Fig. 3. Generalized representation of the effects of temperature and precipitation on the difficulty of developing sustainable agricultural systems (from Stewart et al., 1991).

the soils inherently contain less organic matter and there is less vegetation to help control erosion.

In addition to the greater impact of hot and dry conditions on the degrading processes, these conditions also limit the effectiveness of some conservation practices for sustaining productivity. For example, management practices associated with conserving crop residues are recognized for their effectiveness for controlling erosion and retarding the rate of organic matter decline. However, residue availability decreases sharply in hot and dry regions, which can lead to the negative processes outweighing the positive practices, thus resulting in a sharp drop in soil productivity.

Besides low production in semi-arid regions, residues often are used for livestock feed, fuel, shelter and manufacturing purposes. Although amounts may be limited, residues have a major influence on soil and water conservation and, hence, on crop production. The objectives of this report are to: (1) illustrate the value of crop residues for conserving soil and water resources and enhancing crop yields; and (2) identify and show the value of tillage and related practices for conserving soil and water resources where adequate residues are not available.

RESIDUE MANAGEMENT EFFECTS

Residue management ranges from complete removal or destruction to total retention, as with no (zero) tillage systems. Residue removal may not be detrimental where the erosion potential and the need for water conservation are low or where alternative practices are employed (see next section). However, in most semi-arid regions, these are great, and the importance of crop resi-

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dues on the soil surface for these purposes has long been recognized (Papendick et al., 1990).

Stubble mulch tillage was developed to control wind erosion in the U.S. Great Plains and is basically a residue management system. With this system, sweeps or blades undercut the soil surface at 5–10 cm to control weeds and to prepare a seedbed for the next crop, but most crop residues are retained on the surface.

Stubble mulch tillage also helps control water erosion, with both surface residues and tillage being involved. Surface residues dissipate the energy of falling raindrops, thus minimizing soil particle detachment, dispersion and surface sealing, thereby maintaining favorable water infiltration rates and minimizing particle transport across the surface. Surface residues also retard water flow across the surface, thus providing more time for infiltration and again minimizing particle transport. Soil loosening by stubble mulch tillage provides for greater water infiltration into soils having dense surface layers. The tillage also roughens the surface and creates depressions for temporary water storage, thereby providing more time for infiltration. This results in reduced water flow and particle transport, thus minimizing erosion.

In addition to reducing erosion, stubble mulch tillage provides water conservation benefits, which increase as the amounts of surface residues increase (Russel, 1939) (Table 1). Water conservation was greatest where 17 Mg ha^{-1} of wheat (*Triticum aestivum* L.) straw was placed on the surface and the soil was not plowed (no tillage) because there was no runoff and evaporation was less than with other treatments. Although the potential for greater water con-

TABLE 1

Water storage, runoff and evaporation from field plots at Lincoln, Nebraska, 10 April to 27 September 1939 (adapted from Russel, 1939)

Treatment	Storage (mm)	Runoff (mm)	Evaporation (mm)	Evaporative loss[1] (%)
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	27	28	266	83
No straw, disked	7	60	254	79
Contour basin listing	34	0	287	89

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

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servation with no tillage was evident from this and other early studies, practical no-tillage systems were not available at that time because of weed control and equipment operation limitations. Since then, major advances in chemical weed control and equipment have made reduced- or no tillage systems practical for many crop production situations. For a U.S. Great Plains location, progressive increases in soil water storage and wheat yields with changing tillage practices during fallow since 1916 were illustrated by Greb (1979) (Table 2). Retention of more surface residues and improved weed control undoubtedly were the primary reasons for greater water storage, but improved cultivars, pest control, soil fertility and equipment contributed to the higher yields.

In recent years, much research has involved the effects of conservation tillage on soil and water conservation, crop responses and soil properties. In the U.S.A., conservation tillage is defined as any tillage or planting system that maintains at least 30% of the soil surface covered by residues after crop planting to reduce soil erosion by water. Where wind erosion is the primary concern, at least 1.1. Mg ha^{-1} of flat, small grain residue equivalent must be maintained on the surface during the critical erosion period (CTIC. 1990).

According to Van Doren and Allmaras (1978), less than 1.0 Mg ha^{-1} of wheat straw provides 30% surface cover, which in turn reduces soil losses by

TABLE 2

Progress in a wheat-fallow system with respect to water storage and wheat yields, Akron, CO (adapted from Greb, 1979)

	Tillage during fallow[1]	Fallow water storage		Wheat yield ($Mg\ ha^{-1}$)
		(mm)	(% of precipitation)	
1916–1930	Maximum tillage; plow, harrow (dust mulch)	102	19	1.07
1931–1945	Conventional tillage; shallow disk, rod weeder	118	24	1.16
1946–1960	Improved conventional tillage; begin stubble mulch in 1957	137	27	1.73
1961–1975	Stubble mulch; begin minimum tillage with herbicides in 1969	157	33	2.16
1975–1990	Projected estimate; minimum tillage; began no tillage in 1983	183	40	2.69

[1]Based on 14 months of fallow, from mid-July to second mid-September.

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about 70% (Fig. 4). Data in Fig. 4 illustrate that small amounts of residue are highly effective for controlling erosion by wind and water. Because of differences in residue density, different amounts of other crop residues would be required to provide protection equivalent to that provided by wheat straw. For example, 1.0 Mg ha^{-1} of wheat straw provides about 50% surface cover (Van Doren and Allmaras, 1978), but about 3 and 9 Mg ha^{-1} of grain sorghum (*Sorghum bicolor* (L.) Moench) stover and cotton (*Gossypium hirsutum* L.) stalks, respectively, are needed to provide the same percent cover when placed flat on the surface (Unger and Parker, 1976). Sallaway et al. (1988) established relationships between stubble weight (kg ha^{-1}) and surface cover (%). Based on their study, (Projected cover$=m[1-e^{-\text{stubble weight}}]$, with m being 98.1 for wheat, 64.7 for sorghum and 49.3 for sunflower (*Helianthus annuus* L.).

Soil water storage at many semi-arid locations increased with increasing amounts of crop residue maintained on the surface (Unger, 1984; Ojeniyi, 1986; Rasmussen et al., 1986; Al-Darby et al., 1989; Nyborg and Malhi, 1989; Marley and Littler, 1990; Sharma et al., 1990; and others). Greater infiltration, less evaporation, and effective weed control contributed to the higher soil water contents with conservation tillage. In Australia, bare soil or stubble burning as compared with mulching practices resulted in the highest rates and amounts of runoff (Freebairn and Boughton, 1985; Freebairn et al., 1986). Roth et al. (1988) recommended that at least 4–6 Mg ha^{-1} of mulch is needed to reduce runoff and erosion effectively, but such amounts often are not available in semi-arid regions without irrigation, and maximum water conservation may not be achieved. Much lower residue amounts greatly reduce erosion (Fig. 4) because surface residues reduce soil loss much more than they reduce runoff (Harrold and Edwards, 1972; Rockwood and Lal, 1974).

To achieve maximum benefits from the greater infiltration with surface residues, soils must be able to store the water and evaporation must be mini-

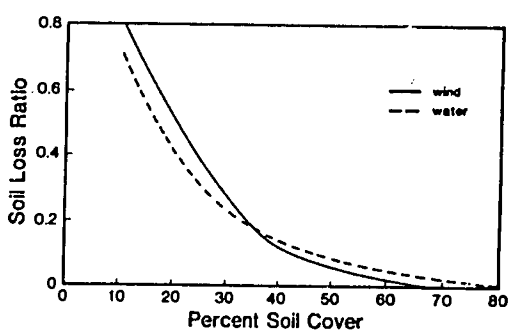

Fig. 4. Relationship between soil loss ratio (SLR is soil loss with cover divided by soil loss from bare soil) and percentage surface cover (from Papendick et al., 1990). Printed from Advances in Soil Sciences with permission from Springer-Verlag, Inc., to use copyrighted material.

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mized. Evaporation following precipitation decreases with increasing amounts of surface residues (Smika, 1976, 1983; Giraldez et al., 1986; Enz et al., 1988). After a 165-mm rain, Smika (1976) compared evaporative losses during the following 34-day period when no additional rain occurred. Treatments compared were conventional (stubble mulch), minimum (stubble mulch plus herbicidal weed control), and no tillage (herbicides only). These resulted in 1.2, 2.2 and 2.7 Mg ha^{-1} of residues, respectively, on the surface during the drying cycle. Water contents to the 15 cm depth were little affected by tillage treatment immediately after the rain, but averaged 0.156, 0.113 and 0.069 kg kg^{-1} to that depth with no, minimum and conventional tillage, respectively, after 34 days. Lower evaporation with surface residues results from reduced surface wind speeds and temperatures than with bare soil (Smika, 1983; Enz et al., 1988).

Evaporation is lower from residue-covered than from bare soil initially and for a time after soil wetting. However, as the surface dries, the evaporation rate becomes lower for bare than for residue-covered soil, which normally remains wetter near the surface for a longer time. As a result, cumulative evaporation for both conditions with prolonged drying becomes similar or may even become greater where residues are present. Prolonged drying may occur where a distinct rainy season is followed by a distinct dry season. To avoid excessive evaporation under such conditions, loosening the soil by tillage decreases evaporation by reducing capillary water flow to the surface (Minhas et al., 1986; Papendick, 1987).

Although conservation tillage compared with conventional tillage enhances water conservation and crop yields in many cases, opposite results or no differences were reported by others (Bhatnagar et al., 1983; Goense, 1986; Rao et al., 1986: Willcocks, 1988; Arora et al., 1991; Singh et al., 1991). In India, irrigated wheat and peanut (groundnut, *Arachis hypogaea*) yields were similar with conventional and no tillage on a sandy soil, but significantly lower with no tillage on a sandy loam soil (Bhatnagar et al., 1983), possibly because the soils had lower water-holding capacity and irrigation negated any slight differences in water storage that may have occurred. Low maize yields with no tillage in Surinam (Goense, 1986) possibly resulted from poor soil drainage, which has an adverse effect on yields under no tillage conditions (Griffith et al., 1988). When conventional and no tillage were alternated from year to year, yield reductions owing to no tillage were reduced (Allen et al., 1976; Unger, 1977; Goense, 1986).

Under semi-arid conditions in India (Rao et al., 1986), conventional tillage was superior to no tillage, reduced tillage, or mulching with sunn hemp (*Crotalaria juncea*) for increasing soil water content and yields of barley (*Hordeum vulgare* L.), mustard (*Brassica juncea*), and chickpea (*Cicer arietinum*) grown in the dry season with conserved soil water. In Botswana, no

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and sweep tillage did not enhance water infiltration and crop yields on clod-forming sandy loam soils. Best results were obtained with precision strip tillage, which was a form of controlled-traffic tillage (Willcocks, 1988). These soils had a high bulk density and a hard surface crust developed following rainstorms, which suggests that they were low in organic matter, surface residues were limited, and substantial degradation had occurred prior to the study. Conservation tillage, especially no tillage, generally is not considered a viable option for crop production on severely degraded soils because of such factors as low soil organic matter concentration, low soil fertility, poor soil physical condition, low water infiltration rate, and poor plant growth (Charreau, 1977; Lal, 1980).

In the studies by Arora et al. (1991) and Singh et al. (1991) in India, no tillage was inferior to most other tillage treatments with regard to soil water contents and crop yields. Low water contents in the upper soil layer resulted in poor yields with no tillage at Varonasi (Singh et al., 1991). At Ludhiana, low water retention, excessive permeability and high mechanical resistance, along with high evaporation, contributed to the poor results with no tillage compared with those resulting from plowing 10, 20 or 30 cm deep (Arora et al., 1991). The amount of residue present was not reported for either study.

Other factors contributing to poor results with conservation tillage include soil compaction, poor weed control, equipment problems, insect and disease problems and poor management. Overall, however, conservation tillage, which is a crop residue management practice, effectively conserves soil and water resources, and sustains soil productivity and enhances crop yields in many situations.

TILLAGE AND SUPPORT PRACTICE EFFECTS

When conservation tillage is not used, either by choice or because of inadequate residues, then soil and water must be conserved by other means. For field crop production, tillage is usually involved, and it may be supplemented by other practices. Tillage without surface residue maintenance is called "clean tillage" and the supplemental practices are called "support practices" (Unger and Stewart, 1988).

Tillage

Soil erosion can be greatly reduced or even eliminated in many situations by the appropriate use of clean tillage. Wind erosion usually can be controlled by tillage that provides an adequately rough or cloddy surface. Ridges formed by tillage can greatly reduce erosion, especially when they are oriented perpendicular to the prevailing erosive winds. Erosion control is further enhanced if cloddy, nonerodible materials are at the surface, which can be achieved with implements such as chisels and lister, sweep and moldboard plows. Harrows (drag and disk) and rotary tillers, which cause surface smoothing and clod breakdown, normally should not be used on soils highly subject to wind erosion. On some soils, for example sandy soils for which surface roughness greatly decreases during major rainstorms, additional tillage is often required after such rainstorms to roughen the surface again (Fryrear, 1990). Effective wind erosion control is usually achieved by using a combination of control methods including roughening the surface, providing for nonerodible materials at the surface, leaving crop residues on the surface, or establishing wind barriers (Fryrear, 1990).

To control water erosion with clean tillage, infiltration must be increased or excess water must be conveyed from the land at nonerosive velocities. This is most often achieved where tillage that ridges or roughens the surface is used in conjunction with graded furrows, contouring, furrow diking (tied ridges), terracing and other practices, which are discussed later.

Temporary surface water storage can reduce runoff and erosion when precipitation rates exceed infiltration rates. Ridge-forming tillage on the contour is a proven water erosion control and water conservation practice. The ridges reduce or prevent runoff, thus providing more time for infiltration, but unless they are level, some water may be lost as runoff and serious erosion may occur in drainage areas. To avoid this, furrow blocking (or tied ridges) can greatly reduce the possibility of runoff, even on gently sloping land. At Bushland, Texas, all water from a 150-mm rain during a 24-h period was retained on the slowly permeable Pullman clay loam (Torrertic Paleustoll) (Jones and Stewart, 1990).

Besides ridge-forming tillage alone or such tillage in conjunction with furrow-diking and other equipment for forming surface depressions, plows (moldboard, disk, sweep), chisels, rotary tillers and cultivators also affect soil pore space and surface roughness and depressions and, therefore, runoff and erosion. On Barnes loam (Udic Haploboroll), different tillage methods affected the potential water storage volume and cumulative infiltration (Table 3). With plowing, cumulative infiltration approached the combined storage volumes before runoff started and exceeded them before 25 mm of runoff occurred. For other treatments, storage volumes were not filled, even though 50 mm of runoff occurred. Smoother surfaces for treatments other than plowing apparently resulted in more rapid soil aggregate dispersion and surface sealing, which reduced infiltration and increased runoff.

In India, tillage improved soil water conditions and crop yields relative to those with no tillage. Under dryland conditions, two diskings improved ger-

TABLE 3

Effect of tillage-induced plow layer porosity and surface roughness on cumulative infiltration of simulated rainfall (from Burwell et al., 1966)

Tillage treatment[1]	Potential water storage volume due to		Cumulative infiltration[3] (mm) to		
	Pore space[2] (mm)	Surface roughness (mm)	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]Plowing and rotovating performed to at 15 cm depth; cultivating to a 7.5 cm depth on untilled soil.
[2]Measured to tillage depth.
[3]Water applied at a rate of 127 mm h^{-1}.

mination, tillering and yields of barley as compared with other less intensive tillage treatments (Singh et al., 1991). The poor response to no tillage was attributed to low water contents in the upper soil layer.

Corn yields increased with depth of tillage on the sandy soils used by Arora et al. (1991), with the effect being greatest on soil having the lowest water-holding capacity (8 mm m^{-1} of soil depth). In addition, there were interacting effects of tillage depth, irrigation amount and frequency, and fertilization. The greater response to tillage depth on the sandier soils resulted from a greater soil volume being made available for root development, which minimized crop water stress. Greater responses to tillage than no tillage or greatly reduced tillage were reported also by Jones (O.R. Jones, personal communication, 1990), Karaca et al. (1988), Prihar and Jalota (1988) and Willcocks (1988) on a variety of soils. In general, tillage disrupted the dense surface crust or plow layer on soils that had low amounts of surface residues. This resulted in increased water infiltration and conservation and/or improved soil physical conditions for crop establishment and growth.

Support practices

Support practices provide soil and water conservation benefits on soils where tillage alone is not adequate. These are usually used in conjunction with tillage, and the benefits are additive in most cases. Support practices for this report are engineering type or cultural practices (other than tillage) that aid soil and water conservation efforts.

Contouring

Contouring involves performing tillage and cultural operations across the slope in rows that are as level as practical. The potential for water erosion from low- to moderate-intensity storms is greatly reduced by contouring when lister or other ridge-forming tillage is used (Stewart et al., 1975). Water conservation is improved also, which can improve crop yields (Patil and Bangal, 1989). However, contouring is ineffective when major storms cause overtopping and breaking of the ridges, which may increase erosion in localized areas. With ridge-forming tillage (for example, lister tillage), each ridge serves as a miniature terrace to hold water on the land. Contouring has little direct value for controlling wind erosion unless the ridges increase surface roughness perpendicular to the prevailing erosive winds or there is no dominant erosive wind direction.

Furrow diking

Furrow diking (tied ridges, basin tillage, furrow damming or blocking) enhances erosion control and water conservation by retaining potential runoff water on the land until it infiltrates. For this practice, small earthen dikes are constructed at 1–4 m intervals between ridges formed by tillage. A variation of furrow diking is basin pitting, which forms depressions on land where ridge tillage is not used (Morin and Benyamini, 1988; Unger et al., 1988). Diking and pitting have potential for increasing yields (Krishna and Gerik, 1988; Morin and Benyamini, 1988; Rodriguez, 1988; van der Ploeg and Reddy, 1988; Williams et al., 1988; Jones and Stewart, 1990), but not when rainfall is adequate to grow crops without water conservation or when there is no runoff (Williams et al., 1988).

Stripcropping

Stripcropping controls water and wind erosion. For water erosion control, alternate cropped and protective strips are usually of equal width, with soil eroded from cropped areas being trapped in protective strips. Stripcropping reduces soil losses from a field, but may not prevent movement within a field unless water flow within the field is retarded by the strips, which could also improve water conservation.

In the U.S.A., stripcropping is widely used to control wind erosion where fallow and cropped strips that are perpendicular to the prevailing erosive winds are alternated. On fallow areas, surface residues help control erosion by reducing field length in the direction of the prevailing winds. In other cases, narrow strips of plants (barriers) help control wind erosion and have conserved water (Bilbro and Fryrear, 1988; Wolde and Thomas, 1989; Fryrear, 1990). The area protected by barriers is usually about 10 times as wide as the height of the barrier (Bilbro and Fryrear, 1988).

Terraces

Level terraces are constructed across the slope to retain water on land. They often have blocked ends to reduce or prevent runoff, thus providing more time for infiltration and enhancing water conservation. Graded terraces convey runoff water from land at nonerosive velocities. They are constructed with a slight gradient in the terrace channel and usually are used in conjunction with waterways or underground outlets to convey excess water from fields safely. The effectiveness of terraces for conserving soil and water usually can be enhanced when they are used in conjunction with contouring, diking, conservation tillage and stripcropping (Unger and Stewart, 1988).

With level terraces, water is often concentrated in terrace channels, which can interfere with cultural operations and adversely affect crop growth and yields. The water concentration problem is minimized or avoided when bench or conservation bench terraces are used. Both types require land leveling. With bench terraces, the entire terrace interval is leveled and water is retained uniformly on the bench. In contrast, usually only one third or one half of the inter-terrace interval of conservation bench terraces is leveled, and leveling costs are less than for bench terraces. A further reduction in leveling costs can be achieved by constructing narrow bench or conservation bench terraces (only wide enough to accommodate one or two passes with equipment being used) (Jones, 1981).

Diversion terraces consist of ridges and channels constructed across the slope to protect fields against runoff from unprotected areas, divert water from gullies, or protect farm improvements and structures (fences, roads, buildings, etc.). They are often used to prevent runoff from entering terraced fields.

Graded furrows

Whereas contour furrows minimize runoff and erosion, graded furrows convey excess water from fields at nonerosive velocities, with each furrow serving as a miniature graded terrace. Although designed for water removal, graded furrows may conserve water because of more uniform water distribution over the entire field.

Other practices

A variety of soil and water conservation practices are available. Some of these are discussed briefly with some references given for further information.

Water harvesting. With this practice, runoff from parts of the land area supplements the water supply for crops on a smaller part of the total area. The water may be directly diverted to the cropped area or stored in ponds, then used to irrigate crops at critical growth stages (Anaya-Garduno, 1988; Carmona and Velasco, 1988; Carter et al., 1988; Perrier, 1988; Zaonga et al., 1988; Critchley, 1989; Agrawal, 1990).

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Slot or vertical mulch. With slot mulching, the crop residues remaining after harvest are packed into a continuous slot on the contour. The practice was designed to maintain open channels for water flow into frozen soils (Unger et al., 1988), but should also enhance deeper water storage on other soils where adequate residues are available. Placing gypsum in slots also was shown to increase water infiltration (Jayawardane and Blackwell, 1986). Vertical mulching is similar to slot mulching, with various materials having been used to fill the slot, but the slot may not remain open to the surface because of tillage over the slot.

Deep tillage. Tillage to depths greater than 25 cm has variable effects on soil water contents and crop yields, with yields generally increasing when soil conditions that cause problems (high density, high strength, salinity, high erodibility, low infiltration, etc.) are adequately altered by the operation (Unger, 1979; Ike, 1987; Mead and Chan, 1988; Spoor and Berry, 1990; Arora et al., 1991).

Limited irrigation–dryland farming system. With this system, the use of growing season rainfall, which varies from year to year, and a limited irrigation water supply, which is fixed for a given year, is maximized for crop production. The system is self-adjusting and results in more of the land being irrigated in years of above-normal than in below-normal rainfall (Stewart et al., 1983).

Row spacing. For most crops, row spacings within a certain range have little or no effect on yields, but spacings below or above the range may greatly reduce yields (Gallez and Mockel, 1988; Muller and Du Preez, 1988; Nunez et al., 1988). However, a 2.0 m spacing for maize resulted in yields similar to those with 1.0 or 1.5 m spacings, apparently because the wide spacing resulted in a soil water reserve for late-season crop use (Muller and Du Preez, 1988).

Drainage. Excess water usually is not a problem in semi-arid regions, but can be a problem in localized areas or in unusually wet seasons. Where it is a problem, terraces (graded and diversion) and graded furrows can remove the excess surface water or divert it from low-lying areas. Other practices include establishing waterways to drain low-lying areas and ridges on which to plant crops (Unger and Stewart, 1988).

In summary, the main objective when clean tillage is used is to provide soil conditions that reduce runoff and soil particle movement to control water erosion, and result in adequate surface roughness (ridges or non-erodible materials) to control wind erosion. The resultant condition should be conducive to storing water for crop use and provide favorable soil conditions for crop establishment, growth and yields. Tillage alone is satisfactory for these purposes under some conditions. Under others, support practices are needed to provide additional benefits. Support practices must be carefully selected and used to overcome a recognized problem. No support practice is expected to be beneficial under all conditions.

PRACTICES TO HELP MEET DEMAND FOR RESIDUES

Crop residues have potential for enhancing soil and water conservation and, hence, sustaining soil productivity and enhancing crop yields. However, in semi-arid regions without irrigation, the amounts of residue produced are often limited and, in many cases, they are used for feed, fuel and shelter. In this section, management practices to meet the demand for crop residues are discussed relative to maintaining adequate amounts on the land for soil and water conservation.

Limited residue removal

The amount of surface residue needed to reduce erosion greatly is relatively low (Fig. 4). Unless practical alternatives are available, adequate residues should be retained on the land to control erosion. When residues exceed the amount needed for the selected level of erosion control, the excess could be removed and used for other purposes. Certainly, the type of material must be considered. Also, the amounts shown may not prevent erosion, but erosion control and usually water conservation improve with increasing amounts of surface residues.

Selective residue removal

Crop residues include leaves, stems, chaff, seed heads and root crowns with some being of greater value for a given purpose than others. Hence, removing only the most valuable type for a given purpose would allow others to be retained on the land for conservation purposes. Other types of selective removal include using only the plant materials that pass through the harvester as feed; allowing animals to forage on fields after crop harvest, but removing them while adequate residues still remain; and removing residues only from less erodible areas while retaining most on the more erodible areas within a field.

Substitute high-value forages for residue

After grain harvest, residues of crops such as wheat, sorghum, maize and sunflower have limited nutritive value for animals. In contrast, forage crops harvested at the optimum stage have a much higher nutritive value. Consequently, growing some high-value feed crops could permit the use of residues from grain crops for conservation purposes. Animal production would not decrease, and may increase if adequate high-value feed is produced. Areas for other crops would decrease, which may initially decrease production of these crops. However, if the residues of those crops are effectively managed, it can improve soil and water conservation and nutrient cycling, which, in turn, can significantly increase crop yields (Papendick and Parr, 1988).

Alley cropping

With alley cropping, deep-rooted perennial shrubs or trees are grown in rows spaced far enough apart so that crops can be grown in the interrow area. Pruning the shrubs or trees at the start of and periodically during the growing season minimizes competition for light and water. Pruned leaves and twigs are used as a mulch for the cropped area or as animal feed. The mulch helps control weeds and recycles nutrients. Woody materials are used as fuel. For maximum benefit, selected species should grow rapidly, fix nitrogen, have a multipurpose nature, and have a deep, narrow root system to minimize competition for water and nutrients. The legumes *Leucaena leucocephalia* and *Gliricidia* sp. have performed well under some conditions (Wilson et al., 1986; Atta-Krah, 1990), but serious competition for water decreased sorghum, cowpea *(Vigna unguiculata)* and castor (*Ricinus sativa*) yields in India (Singh et al., 1988).

Utilization of wasteland areas

Land unsuitable for field crop production is located on many farms and in or near villages or communities. It may be adjacent to waterways, on rocky outcrops, in low-lying areas and along property lines. Some such land is used to grow plants that provide feed, fuel, or shelter materials, but further development for these purposes could reduce the demand for crop residues. Improved management could also increase their value for controlling erosion.

Balancing feed supplies and animal populations

A proper balance between available feed supplies and animal populations could decrease the demand for residues as animal feed and still provide some residues for resource conservation purposes. Serious land degradation owing to long-term overgrazing and/or excessive residue removal for feed has occurred in many cases (Papendick and Parr, 1988). Social, economic and agricultural factors are involved, and these must be considered when implementing changes to improve the feed supply–animal population balance. In

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some cases, changes in national policies and priorities also may be needed to improve the balance.

Using alternative fuel sources

Most semi-arid regions have an abundance of sunshine, which provides an inexhaustible supply of solar energy during a large part of the year. Solar units for water and space heating and crop drying are used in some countries, but their use is limited or nonexistent in others. Solar energy may not be available during cloudy weather, but use when available could reduce the demand for residues as fuel. Also, wind energy is abundant at times in many regions and, if properly harnessed, could provide energy for various purposes, thus again freeing residues for other uses. In either case, social, economic and governmental factors must be considered when implementing the use of these energy sources, and technical advances may be required to develop practical solar or wind energy units, especially for food preparation.

GENERAL SUMMARY AND CONCLUSIONS

Soil degradation is prevalent in many semi-arid regions. To avert further degradation, the soil productivity balance must be shifted from degrading processes to conserving practices. Two soil conserving practices are residue management and conservation tillage. When adequate amounts are retained on the soil, crop residues are highly effective for controlling erosion by wind and water, and have greatly enhanced water conservation and crop yields in many cases. A major limitation to residue use for conservation purposes in many semi-arid regions is low residue production. This is compounded by residue removal for feed, fuel and shelter in many countries.

Where residues are limited or not managed on the surface, clean tillage alone or in conjunction with various support practices must be relied upon for soil and water conservation purposes. The tillage and support practices should provide an adequately rough, non-erosive surface to control wind erosion, and reduce runoff amounts and velocities to control water erosion. When runoff is reduced, soil particle transport is usually reduced to a greater extent. Runoff reduction also increases the potential for water conservation, which is of major interest in semi-arid regions where crops are grown without irrigation.

Because of the competition for crop residues in many cases, management options, if implemented, could reduce the demand for residues, yet provide some residues for other purposes or provide alternatives to the use of residues in some cases. These options include limited residue removal, selective residue removal, substituting high-quality forages for residues, alley cropping, using wasteland areas, balancing feed supplies and animal populations, and using alternative fuel sources.

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