1

Water Conservation for Agriculture

Paul W. Unger
retired, formerly USDA-ARS, Conservation and Production Research Lab., Bushland, TX

Mary Beth Kirkham
Dep. of Agronomy, Kansas State University, Manhattan, KS[1]

David C. Nielsen
USDA-ARS, Central Great Plains Research Station, Akron, CO

The importance of water conservation for agriculture has been recognized for centuries. Bennett (1939), in his book *Soil Conservation*, cited numerous examples from ancient times of countries where canals were developed to convey water to agricultural lands for improved crop production. In addition, reservoirs were constructed for retaining water for later use on agricultural land, terraces were constructed to reduce runoff, plowed fallowing was promoted to conserve water, deep plowing was used in some cases, and contouring was used to retain water on land. Water conservation seldom was the direct object of these practices, but water conservation was achieved by using them.

Water for agriculture is derived from precipitation or from a stream, reservoir, or aquifer where irrigation is practiced. Precipitation frequency in humid regions usually is adequate to provide for plant needs, but even in such regions, precipitation amount and distribution vary considerably from average in any given year. For example, at Watkinsville, GA (all locations and cites mentioned are in the United States unless noted otherwise), where annual precipitation averages 1245 mm, 14-d droughts average three per year, which may severely reduce crop yields. Water conservation, therefore, is important under such conditions (Barnett, 1987). In contrast, excess water is a problem in some situations, and drainage is required for successful crop production.

Precipitation frequency and reliability decrease when going from humid to subhumid, semiarid, and arid regions, thus increasing the importance of water conservation for successful agriculture in the drier regions. Some crops in humid, subhumid, and semiarid regions and most crops in arid regions are irrigated. For successful crop production under all conditions, adequate water must be stored in soil to sustain crops until the next precipitation or irrigation event. Even when using drip or sprinkler irrigation to apply water frequently, water is temporarily held in soil until used by plants.

Even with irrigation, water conservation is important in many cases because supplies are limited or being depleted, with the latter being the case

[1] Contribution no. 08-166-B from the Kansas Agric. Exp. Stn.

Soil and Water Conservation Advances in the United States. SSSA Special Publication 60.
T.M. Zobeck and W.F. Schillinger, editors. © 2010. SSSA, 677 S. Segoe Rd., Madison, WI 53711, USA.

for portions of the Ogallala Aquifer in the Great Plains (Stewart, 2003) and for aquifers in China and India (Unger et al., 2006). Water conservation is also important because competition for fresh water is becoming an increasingly important issue among nations, geographical regions, and segments of society, including agricultural, urban, industrial, and recreational users (Unger and Howell, 1999). This is a major issue in some regions where the supply is naturally limited and where the growing needs of other users already often clash with agriculture for available supplies (Kuhn et al., 2007; Levy, 2003; Rothfeder, 2001). Water conservation is also more important than ever because of the increasing amount needed to produce the food, fiber, and fuel for the ever-increasing world population.

Research on water conservation for agriculture has been extensive throughout the past 100 years. It has been conducted at numerous colleges and universities and at state, federal, and private research facilities. The 1907 USDA Yearbook contains a list of "Agricultural Experiment Stations in the United States, Their Locations, Directors, and Principal Lines of Work" (USDA, 1908). The list identifies the main experiment station in the different states, but outlying experiment stations were also established at which agronomic research was conducted in many states. Agronomy is listed as a "principal line of work" at most stations. Although agronomy involves many disciplines related to soils and plants, water is a key factor where these entities meet—that is, water is essential for plants grown in soils. While water conservation and use may not have been the direct object of the agronomic research and, therefore, was not reported, water undoubtedly affected the results in many cases.

Early USDA research involving water in soils or for agriculture was conducted by scientists in the Bureau of Soils and the Bureau of Plant Industry (Landa and Nimmo, 2003). By 1914, the USDA Division of Dryland Agriculture had established 22 dryland experiment stations in the Great Plains (Burnett et al., 1985). The initial research at these stations focused on evaluating crops and crop varieties for suitability to a given area. The vagaries of climate and potential for erosion on many soils were recognized, and the research was directed toward developing crop rotations and management practices to control erosion and maximize dryland crop production. The research often was not on water conservation and usually was not reported as such, but when erosion is controlled, water conservation often is achieved through improved plant growth and reduced runoff. Also, although this research was conducted at dryland stations, the results obtained often were applicable to rainfed agriculture at more humid locations.

In addition to formal research at state, federal, and private facilities, efforts of land managers, namely, farmers, have contributed significantly through individual observations and management strategies to achieve water conservation under various conditions.

Our objectives were to review progress that has been made in our understanding of factors affecting water conservation during the past 100 years and to identify some challenges and opportunities for achieving improved water conservation for agriculture. To illustrate the progress, we review practices developed through the years and comment on their effectiveness for conserving water and achieving greater or more reliable crop production.

Primary Areas of Water Conservation

The principles of water conservation for agriculture are the same whether crop production is under rainfed or irrigated conditions. Water must be captured, retained, and used efficiently for producing a desirable yield. These principles have been recognized for many years. Numerous land, climate, social, and environmental conditions and applied practices affect water conservation (Unger, 2006).

Water Capture

Shaw (1911) and Widtsoe (1920) recognized the need to capture, retain, and efficiently use water derived from precipitation. At that time, however, the primary means of managing water was via plowing. According to Shaw (1911), for example,

> *The dominant idea in dry farming is in a sense two-fold. It seeks to secure to the greatest extent practicable the conservation and also the accumulation of moisture in the soil. To accomplish this end, the soil is stirred deeply, whether by the aid of the plow alone or by following the plow with a subsoiler, or by using some other implement, as the deep tilling machine. The ground is compressed subsequent to plowing, and dust mulch is maintained on the soil surface. The increase of organic matter in the soils is also sought.*

Although this quotation pertained to "dry farming," the information undoubtedly was applicable to most agriculture at that time.

Water capture is the first step in water conservation, and Shaw (1911) promoted more frequent and deeper plowing, believing that it would increase water storage in soil. Frequent plowing resulted in the surface being devoid of plant residues, and soil crusting after rains was common. Plowing disrupted the crust and possibly reduced runoff at the next rain, but each plowing undoubtedly further aggravated the crusting problem. In the United States, emphasis on plowing to achieve water capture was largely a carryover from practices that settlers had used in their home countries. Plowing also was the primary method of weed control at that time.

Infiltration

Frequent and deep plowing as proposed by Shaw (1911) had potential for capturing and storing water, provided the soil surface was adequately stable to avoid aggregate disintegration, surface sealing, and excessive runoff, thus resulting in favorable water infiltration into soil. Rainfall energy strongly influences aggregate dispersion and surface sealing, thereby also strongly influencing infiltration (Eigel and Moore, 1983; Giménez et al., 1992; Loch, 1989). Bare soil surfaces resulting from frequent and deep plowing as proposed by Shaw (1911) were unprotected against the impact and energy of falling raindrops, which disrupted soil aggregates and thereby undoubtedly led to restricted infiltration. Besides passing through the surface soil, water must penetrate to adequate depths for storage in the zone from which plants use it. Vertical distribution, namely, water penetration to depths below the surface layer, is part of the infiltration process.

Water infiltration into soil is a complex process that involves saturated and unsaturated flow. The initial stage involves unsaturated flow that is driven primarily by the attraction of water to dry soil particles and the surface tension of water held in the spaces between the particles. Gravity and soil solute content also

affect unsaturated water flow (Hillel, 1998). Water flow in soil pores due to surface tension is known as *capillarity* and was already recognized in the early 1900s by Briggs and McLane (1907) and Buckingham (1907). Unsaturated flow dominates infiltration as long as the application rate (e.g., precipitation rate) does not cause water ponding on the surface. When the application rate exceeds the unsaturated flow rate, saturated flow becomes dominant. Saturated flow is dominant unless water application (e.g., precipitation) is of low intensity or short duration, or for coarse-textured soils in which water flow is rapid (Baver, 1956).

The loosened soil resulting from frequent and deep plowing as promoted by Shaw (1911) apparently was readily filled with water to the depth of plowing in many cases, but may have adversely affected continued infiltration on some soils. According to Horton (1933), soil surface conditions, namely, at the water–soil contact interface, mainly governs the infiltration rate. Water movement at depths below the surface, however, also is important with respect to infiltration (Baver, 1956; Hillel, 1998; Philip, 1969; Taylor and Ashcroft, 1972; van Bavel and Hanks, 1983). Surface conditions influencing infiltration include soil texture, aggregate size and stability, and water content. Subsurface conditions influencing infiltration include soil texture, water content, structural stability, and horizon characteristics. These influence infiltration through their effect on unsaturated and saturated water flow in the soil profile. When rainfall or irrigation causes water ponding on the surface, entrapped air in soil pores can also reduce infiltration (Dixon, 1966; Wangemann et al., 2000). In contrast, infiltration under ponded water conditions can be greatly enhanced when channels formed by soil fauna (e.g., worms, insects, spiders, etc.) and decayed roots are open to the surface (Cochran et al., 1994; Kladivko, 1994).

Surface Residues

Plowing to "turn under" grasses was used by settlers in the late 1800s and early 1900s to prepare land for crops in the drier regions of the country (e.g., the Great Plains) (Fig. 1–1). Initially, with favorable precipitation, such plowing provided good results, but contributed greatly to the disastrous erosion by wind and dev-

Fig. 1–1. Tillage to "turn under" grasses in preparation for field crop production by early settlers in the Great Plains. Photo: Panhandle-Plains Museum, Canyon, TX.

astation of the land that occurred during the drought of the 1930s (Fig. 1–2). The region most affected was termed the *Dust Bowl* (Bennett, 1939). (Note: For this chapter, we use the Soil Science Society of America [SSSA, 2001] definition of plowing, namely, a tillage operation that is performed to shatter soil with partial or complete inversion at depths usually greater than 20 cm.)

The devastating conditions of the Dust Bowl era led to major land-use changes where the potential for erosion by wind existed, with the realization that crop residues retained on soil were highly effective for controlling erosion. Surface residues also provided water conservation benefits, with Duley and Rus-

Fig. 1–2. (Top) An approaching "dust cloud" during the severe drought of the 1930s in the southern Great Plains. (Bottom) Land devastation caused by severe erosion by wind during the drought of the 1930s. Photos: (top) USDA-NRCS; (bottom) USDA.

sel (1939) being among the first to recognize those benefits. At Lincoln, NE, 54% of rainfall was stored with 4.5 Mg ha^{-1} of flat straw on the soil surface, 34% with straw incorporated into soil, and 20% with a bare surface treatment. Maintaining surface porosity and reducing water flow across the surface with straw were considered major contributors to increased water capture. Duley and Kelly (1939) found that soil surface conditions (cover and aggregate size) affected water infiltration (capture) more than soil surface texture and profile characteristics.

The value of residues for protecting surface aggregates versus their value for reducing water flow across the surface was demonstrated by Borst and Woodburn (1942). In their experiment, plant residues at 4 Mg ha^{-1} were suspended on a screen 25 mm above the surface or placed directly on soil. Runoff of applied water equaled 78% from cultivated, dry, bare (uncovered) soil; 1.7% with residues on the surface; and 1.2% with residues on the screen. They concluded that elimination of raindrop impact on soil aggregates was more important than physical blocking of water across the surface for conserving water. The percentages for the two residue treatments, however, differed only slightly, and flow blocking as considered by Duley and Russel (1939) certainly also was important for conserving water.

When benefits of surface residues for conserving soil and water first became apparent, few tools and techniques were available for producing crops under surface residue conditions. In the 1930s, J. Mack Gowder, a farmer in Georgia, used an implement with a 10-cm-wide chisel point to stir the soil and retain plant residues on the surface. He used the implement, which he called a "bull tongue scooter," in an attempt to mimic the surface cover conditions he observed in a forest on his steeply sloping farm. This method of tillage became known as *stubble-mulch farming*, with that designation being attributed to Dr. H.H. Bennett (Barnett, 1987). Stubble-mulch farming often was (and sometimes still is) referred to as "trash farming" by those who belittled that method of tillage, but it is a highly important practice for conserving soil and water as compared with conditions where clean tillage (i.e., residues plowed under) is practiced.

Stubble-Mulch Tillage

Stubble-mulch tillage (Fig. 1–3) quickly became a recommended conservation practice when the value of keeping the surface covered was recognized. The aim was to keep the soil covered as much of the time as practical to greatly reduce runoff and erosion. Such tillage was the forerunner of today's no-tillage method of farming (Barnett, 1987).

Another Georgia farmer, R. Luther Hardy, used crimson clover (*Trifolium incarnatum* L.) [or ryegrass (*Lolium* spp.)] ahead of summer crops on his good land to achieve soil and water conservation benefits. The clover was partially plowed out in spring to achieve tilled contour strips on which he planted row crops. A 30-cm strip of clover remained between crop rows. Clover was plowed out after setting seed, which provided for a volunteer crop the next year. This tillage system was named the *contour-balk method* and had implications regarding today's method of no-tillage farming (Barnett, 1987). A possible deterrent to using the contour-balk method was competition for water between clover and planted crops (Hendrickson, 1939).

Use of stubble-mulch tillage was promoted primarily for controlling erosion by wind, which was severe during the drought of the 1930s. At that time, the first goal for tillage was to provide a cloddy surface to stop ongoing soil movement

Fig. 1–3. (Top) Stubble mulch tillage being performed after harvest of winter wheat. (Bottom) A sweep on a stubble mulch tillage implement (stubble mulch tillage implements may also have blades instead of sweeps to undercut the soil surface).

by wind. A second goal was use of shallow tillage to control weeds and retain plant residues on the surface to protect the soil from erosion. A third goal was to retain surface residues to reduce runoff, reduce evaporative soil water losses, and conserve more water for the following crop. Various chisel, blade, and sweep implements were developed to achieve these goals (Allen and Fenster, 1986).

When the water conservation (and water capture) benefits of retaining crop residues on the soil surface were recognized (Barnett, 1987; Borst and Woodburn, 1942; Duley and Russel, 1939), extensive research involving stubble-mulch tillage was initiated at many locations, especially in drier regions, and research involving various aspects regarding it continues at some locations. When compared with clean tillage, greater water capture usually was achieved by using stubble-mulch tillage (Black, 1967; Duley and Fenster, 1961; Duley and Russel, 1942; Free, 1953; Greb et al., 1970; McCalla and Army, 1961; Whitfield et al., 1949; Zingg and Whitfield, 1957). The benefits resulted from dissipation of raindrop energy, thus reducing aggregate dispersion and surface sealing; retardation of water flow across the surface, thus providing more time for infiltration; snow trapping; and enhancement of soil organic matter, thus improving soil physical conditions. Infiltration of simulated rainfall increased with increasing organic matter contents and was attributed to increased soil aggregate size (Lado et al., 2004). This demonstrates the importance of favorable soil physical conditions for enhancing water infiltration.

Weed Control

Weed control with chemicals began in the 1800s. Copper sulfate was first used in 1821 (Reinhardt and Ganzel, 2007), and an application of iron sulfate was found to kill broadleaf weeds in 1896 (Tvedten, 2001). The first synthetic organic chemical, namely, 2-methyl-4, 6-dinitrophenol, was introduced in 1932 (Reinhardt and Ganzel, 2007) and a new era of weed control began in 1942 with the development of 2,4-D [(2,4-dichlorophenoxy) acetic acid]. Numerous herbicides are now available, with applications possible before planting or after establishing a crop. Development of effective herbicides has greatly changed crop management practices, which, in turn, has greatly improved water conservation under many conditions. Water conservation resulting from use of herbicides is due to elimination of water use by weeds; less frequent or elimination of tillage for controlling weeds, thus limiting exposure of moist soil to the atmosphere and reducing evaporative water losses; and retaining more crop residues on the surface, thus achieving the water conservation benefits previously mentioned.

Effective weed control, especially during a crop's growing season, is essential for successful crop production. Allowing weed growth, however, can provide protection against erosion under conditions where the soil surface would otherwise be bare, that is, during the interval between crops (Bennett, 1939; Schillinger and Young, 2000). Under such conditions, water conservation could still be achieved through timely termination of weeds (before they produce seed) and their residues may enhance water capture through reduced runoff and improved infiltration. Use of delayed stubble-mulch tillage, which allowed weed growth during part of the fallow period, resulted in soil water contents at wheat planting that were similar to those obtained with use of normal stubble-mulch tillage, which prevented weed growth throughout the entire fallow period (Johnson and Davis, 1972).

Tillage Reduction

With the introduction of herbicides, it became possible to reduce tillage intensity and frequency and sometimes eliminate it for crop production. Systems involving less tillage include limited tillage (McWhorter and Jordan, 1985; Shear, 1985), reduced tillage (Lewis, 1985; Triplett, 1985; Wiese et al., 1985), minimum tillage

(Thomas, 1985; Vyn et al., 1998), ecofallow (Alleman, 1982; Greb, 1978; Wicks et al., 1972), chemical fallow (Fenster et al., 1965; Wiese et al., 1967), and conservation tillage (Allmaras and Dowdy, 1985; Fenster, 1977; Wicks, 1985). *Conservation tillage* is "any tillage sequence, the object of which is to minimize or reduce loss of soil and water; operationally, a tillage or tillage and planting combination which leaves a 30% or greater cover of crop residue on the surface" (SSSA, 2001). Provided the indicated amount of residues remain on the surface, all the above qualify as conservation tillage systems. The ultimate conservation tillage system is *no-tillage*, which is "a procedure whereby a crop is planted directly into the soil with no primary or secondary tillage since harvest of the previous crop; usually a special planter is necessary to prepare a narrow, shallow seedbed immediately surrounding the seed being planted" (SSSA, 2001). With no-tillage (Fig. 1–4), maximum residue amounts remain, thereby potentially providing maximum soil and water conservation benefits.

No-Tillage

No-tillage farming has been used for centuries. For example, Incas in South America planted crops without tillage by making a hole in soil with a stick, putting seeds in soil by hand, and covering seeds with their feet (Derpsch, 1998). The development of effective herbicides through the years encouraged producers to adopt the practice of no-tillage crop production. It achieved a major boost when paraquat [1,1′-dimethyl-(4,4′-bipyridinium)] was developed in the United Kingdom in 1955 (Derpsch, 1998).

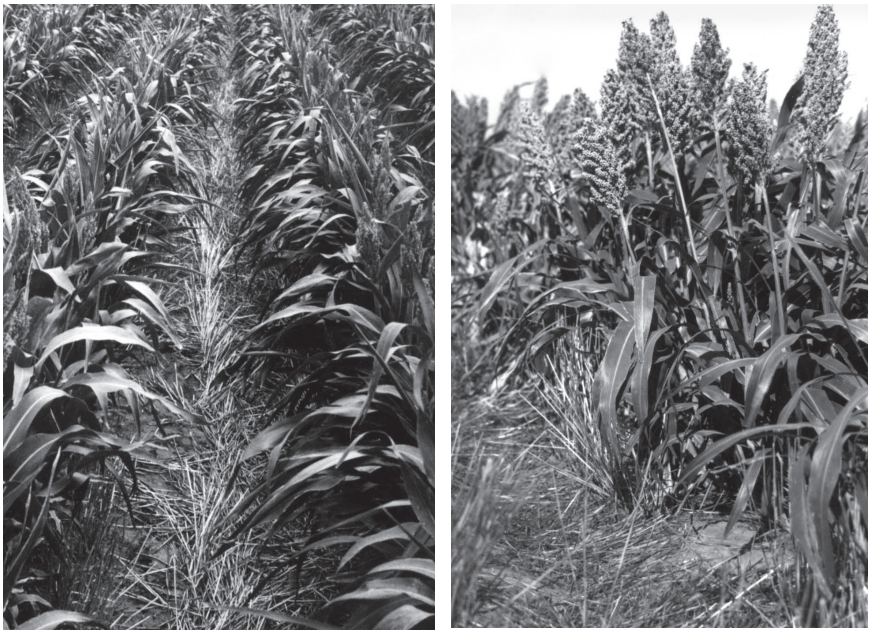

Fig. 1–4. (Left) No-tillage grain sorghum after winter wheat under wheat–sorghum–fallow crop rotation conditions. (Right) Grain sorghum approaching maturity under no-tillage conditions as at left. Note the residues from the previous wheat crop remaining on the surface in both photos.

An estimated 25.2 million ha (22.6% of cropland) were used for no-tillage crop production in the United States in 2004 (personal communication, Frank Lessiter, Editor/Publisher, *No-Till Farmer*, June 2007). In 2004, some form of conservation tillage was used on 41% of U.S. cropland. In Argentina, Brazil, and Canada in 1996–1997, no-tillage use in each country was more than 4 million ha, with lesser but significant amounts in several other countries (Derpsch, 1998).

Water conservation generally is improved by using no-tillage, according to numerous reports in the literature, but we will give only a few examples. At Blacksburg, VA, from 1960 to 1965, available soil water content to 15- and 46-cm depths was greater each year with no-tillage than with conventional tillage (Shear, 1985). At Bushland, TX, in the southern Great Plains from 1979 to 1981, soil water contents averaged 149 (c)[2], 179 (b), and 207 (a) mm with moldboard plowing, sweep tillage, and no-tillage treatments, respectively, at planting time for dryland grain sorghum [*Sorghum bicolor* (L.) Moench]. The water storage occurred from the time of wheat harvest in June until sorghum planting in May or June of the following year. Subsequent grain yields averaged 2.6 (b), 2.8 (b), and 3.3 (a) Mg ha^{-1} for the respective treatments (Unger, 1984). For a wheat (*Triticum aestivum* L.)–fallow study in western Nebraska, infiltration of 76 mm of simulated rainfall was 41, 97, and 99% with plow, stubble-mulch tillage, and no-tillage treatments, respectively, during the fallow-after-harvest phase (October) of the cropping system. In the wheat phase at that time in the rotation, wheat plants were 10 cm tall, and infiltration was 42, 66, and 95% with the respective treatments (Dickey et al., 1983).

As indicated by these examples, soil water contents and infiltration amounts were greatest with no-tillage, which retained more residues on the surface than other treatments. No-tillage, however, does not always result in the most infiltration from a given precipitation event (Jones and Popham, 1997; Unger, 1992). Infiltration may be greater into a tillage-loosened soil than a no-tillage soil when precipitation amounts do not exceed the temporary storage capacity of the loosened soil layer. Also, infiltration into a tillage-loosened soil may be greater when the water content of no-tillage soil is already high when precipitation occurs, thereby resulting in limited opportunity for additional water storage, which was the case on Pullman clay loam (fine, mixed, superactive, thermic Torrertic Paleustolls) at Bushland. Even so, soil water contents at planting of winter wheat and grain sorghum were greater with no-tillage than with stubble-mulch tillage (Jones and Popham, 1997).

Although no-tillage provides conditions more conducive for conserving soil and water than other tillage methods, no-tillage with respect to soil water conditions may not be best for all conditions. For example, it generally is not well-suited to poorly drained soils because the additional water aggravates the excess water problem, thus often reducing yields (Amemiya, 1977; Griffith et al., 1977; West et al., 1996). On hardsetting soils, infiltration may be lower with no-tillage than with soil-loosening tillage (Doyle, 1983; Huxley, 1979; Nicou and Chopart, 1979; Wockner et al., 1996).

Deep Soil Loosening

Use of no-tillage involves minimal soil disturbance and effectively conserves water, but soil loosening and even deep loosening as promoted by Shaw (1911)

[2] Values followed by the same letter in parentheses are not significantly different at the 5% level, Duncan's Multiple Range Test.

has improved water infiltration and conservation under some conditions. Deep loosening of soil by plowing, vertical mulching, or profile modification received considerable interest starting in the 1960s. Use of these practices improved water capture and/or use on slowly permeable, swelling clay soils (Allen et al., 1994, 1995; Burnett, 1969; Burnett and Hauser, 1967; Burnett et al., 1974; Eck and Taylor, 1969; Hauser and Taylor, 1963, 1964; Musick et al., 1981). Deep plowing or profile modification also improved water capture and/or use on soils that have a fragipan (Bradford and Blanchar, 1977), a shallow clay layer (Greb, 1970), coarse surface materials underlain by a heavy clay (Miller and Aarstad, 1972), hard-setting properties (Mead and Chan, 1988), a claypan (Fehrenbacher et al., 1958), or saline conditions (Bowser and Cairns, 1967; Harker et al., 1977; Travis et al., 1990). Soils having a hardpan, plow pan, indurated horizon, or other compacted condition relatively near the surface usually can be improved with respect to water capture by a less intensive operation such as subsoiling, chiseling, ripping, or paraplowing (Baumhardt et al., 1992; Mahler et al., 2003; McConkey et al., 1990; Mukhtar et al., 1985; Pikul et al., 1992, 1996; Steppuhn et al., 1995). These operations loosen the soil, usually to depths greater than normal tillage or plowing, without inverting the surface layer or causing major mixing of the soil horizons.

The above practices improved water capture by increasing infiltration of rain, irrigation, or snowmelt water. To remain effective, loosened soil must remain "open" at the surface to allow water to readily enter it. Use of deep tillage or profile modification is appropriate only when a known adverse soil condition is present (Unger, 1979). Likewise, subsoiling, chiseling, ripping, or paraplowing are appropriate only when a known adverse condition is present. When profile conditions exist that adversely affect water infiltration and crop production, deep plowing or profile modification may be appropriate if the resulting benefits are long-lasting because performing those operations is costly. For example, the benefits of deep loosening Pullman clay loam were still observed after more than 20 yr. Irrigation water (240 mm) infiltrated an unmodified Pullman profile in 28.6 h as compared with 8.4 and 6.3 h for profiles modified to 0.9- and 1.5-m depths, respectively, 26 yr earlier (Unger, 1993). Likewise, moldboard plowing the Pullman soil 0.4, 0.6, or 0.8 m deep in 1966 was still effective for increasing irrigation water infiltration for winter wheat crops from 1988 to 1992 after loosening the surface layer to a 0.2-m depth (Allen et al., 1995). Also, infiltration was still greater in 2005 for Pullman soil plowed 0.7 m deep in 1971 than for soil not deeply plowed (Baumhardt et al., 2008). The continued benefits indicate that the high cost of deep plowing Pullman soil can be recovered with time.

Soil Surface Alterations

The above tillage practices enhanced water capture mainly by providing conditions conducive to more rapid water infiltration. Another approach is to prevent runoff or reduce the runoff rate, thus providing more time for infiltration, which is achieved in many cases when using conservation tillage, especially no-tillage, or by altering the soil surface.

Longer water retention on the surface can be achieved by a variety of practices. These range from changing tillage direction relative to slope of the land to major operations such as terracing and land leveling (Unger, 2006).

The most basic practice for reducing the runoff rate is *contour tillage* (Janick, 2002), which involves tillage across (perpendicular to) the slope of land (Fig. 1–5).

Fig. 1–5. (Top) cotton growing under contour-tillage conditions. (Bottom) Water retained on ridge-tilled, furrow-diked land under contour-tillage conditions. Photo: O.R. Jones, USDA-ARS, Bushland, TX.

Contour tillage has a long history, and was promoted initially for controlling erosion by water (Bennett, 1939). Its water retention benefits are increased by using tillage methods that create ridges across the slope. *Lister tillage*, which forms relatively high ridges with a tool that turns soil laterally in opposite directions from the furrow being formed, is highly effective for retaining water (Fig. 1–5), but its effectiveness generally greatly decreases after crops are planted or cultivated

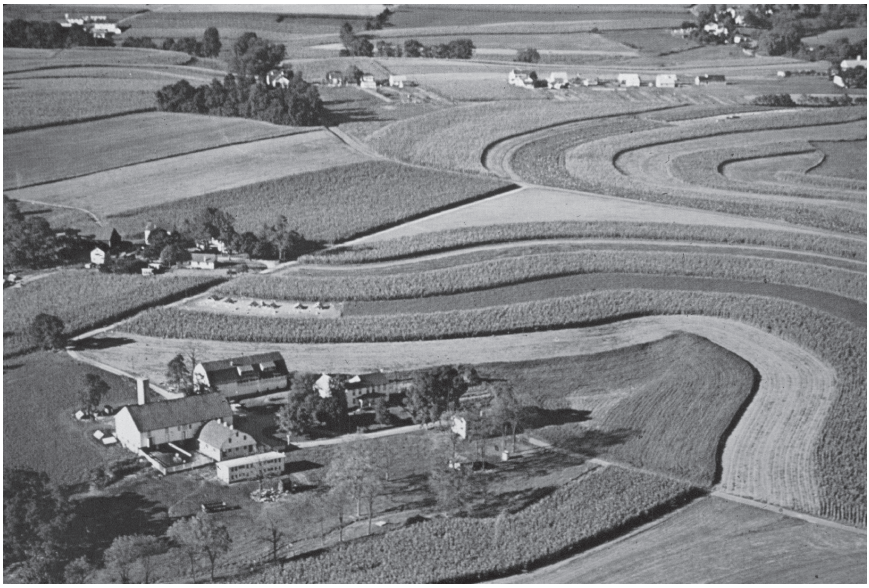

Fig. 1–6. Strip tillage is being used in some fields in the photo.

(Bennett, 1939). Use of reduced tillage along with effective herbicides, which is now possible, should help maintain the effectiveness of lister tillage for a longer time. When used in conjunction with contouring, lister tillage effectively retains water on the land. However, because it is a type of clean tillage, soil aggregate dispersion and surface sealing may occur due to raindrop impact, thus resulting in water ponding in the furrows. As a result, much of the retained water may evaporate rather than infiltrate into some soils.

Contour tillage is best suited for use on gently sloping land. A variation of contour tillage that can be used on somewhat more steeply sloping land is *strip cropping,* in which alternate strips of sod and row crops are planted along the contour (Fig. 1–6). Sod strips with their high absorptive capacity help slow runoff (Janick, 2002). This practice probably was brought to the United States by farmers from Europe (Bennett, 1939).

Except on soils having an extremely uniform slope, it is difficult to uniformly retain water throughout the length of lister furrows. More uniform water retention is obtained by using furrow diking (also known as furrow damming, basin tillage, basin listing, tied ridges, or microbasin tillage) along with ridge-forming tillage (Fig. 1–7) (Bennett, 1939; Clark and Jones, 1981; Gerard et al., 1983, 1984; Jones and Clark, 1987; Krishna et al., 1986).

Furrow diking was originally used in the United States in the 1930s, but was generally abandoned by the 1950s because of slow operation of diking equipment, poor weed control, difficulty in performing cultural operations, and limited yield benefits (Jones and Clark, 1987). Interest reoccurred in the 1970s and 1980s when improved equipment and weed control methods became available, which led to its use during the crop growing season rather than mainly during fallow before crop planting and, in turn, to improved water conservation and crop yields (Clark and Jones, 1981; Gerard et al., 1983, 1984; Jones and Clark, 1987; Krishna et al., 1986).

Fig. 1–7. (Top) Water retained on land where furrows are diked and flowing from land from undiked furrows (instrument measures runoff from undiked furrows) (photo source: O.R. Jones, USDA-ARS, Bushland, TX). (Bottom) A furrow-diking implement.

Where use of contour tillage, furrow diking, or strip cropping does not adequately control runoff, some major soil surface alterations may be required to achieve the desired level of runoff control. Undoubtedly, the most widely used such practice worldwide is *terracing*, in which the interval between adjacent terraces is leveled. This is an ancient practice not widely used in the United States, mainly because of the high cost of land leveling. *Conservation bench terraces* (CBTs), developed in the United States, require leveling only a portion of the land between

adjacent terraces (Hauser and Zingg, 1959; Zingg and Hauser, 1959). At Bushland, for example, only the lower one-third of the interval between terraces was leveled. Runoff from the unleveled (watershed) area averaged 28 mm and was captured on the leveled area. With the 2:1 watershed/bench area ratio, runoff along with precipitation retained on the bench resulted in an average of 84 mm more water available on bench than on watershed areas. The additional water made annual cropping possible on benches, whereas cropping on watersheds involved fallow between successive crops. Conservation bench terraces having various watershed/bench area ratios have been evaluated at several locations (Armbrust and Welch, 1966; Cox, 1968; Hauser and Cox, 1962; Mickelson, 1968). Effectiveness of CBTs with different ratios depended on the potential for runoff and the infiltration and water holding capacity of the different soils. Because land leveling of large areas is costly, Jones (1981) developed CBTs with benches being equal to one width of tillage equipment, thus decreasing the cost of leveling.

Use of graded and level terraces increases soil water storage relative to that achieved without terracing (Dickson et al., 1940; Finnell, 1944). Use of level terraces with blocked ends in conjunction with contour tillage was especially effective for increasing water storage (Burnett and Fisher, 1956; Dickson et al., 1940; Fisher and Burnett, 1953), but water had to be drained from terraces during wet periods to avoid damage to crops (Harper, 1941). Hauser et al. (1962) found that using open-end level or graded terraces resulted in similar crop yields and, therefore, suggested using open-end level terraces, thus avoiding the need for drainage and for constructing high terrace ridges to retain large volumes of water. Use of graded terraces along with graded furrows slows runoff, thus helping to conserve soil and water (Hauser et al., 1962; Richardson, 1973).

Water harvested from land unsuitable for crops can improve crop production on nearby lands. For example, constructing level pans in broad natural waterways and intercepting and spreading runoff water that normally flowed through them resulted in soil water contents at grain sorghum planting time being 96 mm greater on leveled than on unleveled areas (Mickelson, 1966). At forage sorghum (*Sorghum* spp.) planting time, the increase on leveled areas was 58 mm. In both cases, yields were greater on leveled areas. Although water harvesting results in greater soil water contents and crop yields, it is applicable to relatively small areas and has not been widely adopted for general crop production purposes.

Snow Management

A significant portion of precipitation in northern regions is derived from snow. Where water is limited, as, for example, in the Great Plains, the Pacific Northwest, and the Canadian Prairie Provinces, management to capture snow and snowmelt is highly important with respect to water capture and crop production. Because snow often is accompanied by wind, practices to capture snow are similar to those for controlling erosion by wind. Favorable snow and snowmelt capture have been obtained by using standing crop residues, strip cropping, tall wheatgrass [*Thinopyrum ponticum* (Podp.) Barkworth & D.R. Dewey] barriers, wheat stubble strips, or artificial barriers (Aase et al., 1976; Campbell et al., 1992; Greb, 1975, 1980; Greb and Black, 1971; Maulé and Chanasyk, 1990; McConkey et al., 1997; Nielsen, 1998; Pikul et al., 1996; Steppuhn and Waddington, 1996). Deep soil loosening (ripping) improved water capture from snowmelt on frozen soils (Pikul et al., 1996; Zuzel and Pikul, 1987), but ripping a dry pulverized soil provided little benefit with regard to

improving snowmelt infiltration (Pikul et al., 1996). Use of slot mulching, which consisted of packing crop residues into 20-cm wide and 20- to 25-cm deep trenches spaced 2.5 m apart on the contour, reduced runoff from frozen soil compared with that from a no-tillage, non-slotted wheat stubble area (Saxton et al., 1981).

Irrigation Method

In general, practices effective for capturing water from precipitation are effective also for capturing irrigation water. Irrigation methods, however, may strongly influence the amount of applied water that infiltrates the soil.

Irrigation methods are flooding, furrow, sprinkler, Low Energy Precision Application (LEPA) (Fig. 1–8), and drip (surface and subsurface) or some variation of these methods (Howell and Evett, 2005). When using flooding or furrow irrigation, soil permeability and water application rate and duration must be considered to achieve maximum capture of applied water. On moderately and highly permeable soils, water should be applied at a relatively high rate to wet the intended area in a relatively short time. Kemper et al. (1988) used surge irrigation to reduce excessive infiltration into a silty loam. *Surge irrigation* is "a surface irrigation technique wherein flow is applied to furrows (or less commonly, borders) intermittently during a single irrigation set" (SSSA, 2001). Lower application rates and longer times are used on slowly permeable soils, but irrigation efficiencies may be low with furrow irrigation under some conditions (Musick et al., 1988). Furrow irrigation was dominant in the Texas High Plains until 1974 when its use began to decline. Sprinkler irrigation became dominant in the region after 1979 (Musick et al., 1988). Sprinkler irrigation has been dominant in other regions for many years.

With sprinklers, water is applied either with high, medium, or low pressure equipment with various arrangements of the equipment that affect the area

Fig. 1–8. Water being applied to ridge-tilled, furrow-diked land under Low Energy Precision Application (LEPA) conditions.

covered and how water impacts the soil surface (Howell and Evett, 2005). A disadvantage of using high pressure equipment is high evaporative loss of water under some conditions. Spray losses in Kansas were 12% in 1980 and 16% in 1981 (Steiner et al., 1983); they reported losses ranging to 40% at other locations. Spray losses are reduced by using low pressure systems, but because water is applied to a smaller area, runoff may be greater from slowly permeable soils. Use of the LEPA system essentially eliminates runoff and spray losses when used along with furrow diking, but runoff can be high without furrow diking (Howell and Evett, 2005). Application efficiencies of 95 to 98% are attainable by using LEPA along with furrow diking (Bordovsky et al., 1992; Lyle and Bordovsky, 1981, 1983). Spray and runoff losses are eliminated by using surface or subsurface drip irrigation methods, but percolation losses may be high if the soil water content is maintained at a high level (Howell and Evett, 2005).

Major transport losses are possible from the water source to where it is used under irrigated conditions. Losses may be especially high from unlined channels due to seepage and where phreatophytes extract water from irrigation channels or from streams and other waterways (Unger, 2006). Channel linings of cement or flexible membranes and underground pipelines of cement or polyvinyl chloride (PVC) are highly effective for reducing water transport losses. At the point of distribution, use of gated pipes (aluminum, PVC, or flexible materials) can further reduce losses (Unger and Howell, 1999).

Mulching

Mulching is an ancient practice, "perhaps as old as agriculture itself" (Jacks et al., 1955). It affects water conservation through water capture and retention. With respect to water capture, mulches protect the soil surface against raindrop impact, thereby minimizing aggregate dispersion and surface sealing (Loch, 1989). If porous, such mulches allow direct water infiltration into soil or retard water flow across the surface, thereby providing more time for infiltration.

Many different materials have been used as mulches (Bennett, 1939; Bilbro and Fryrear, 1991; Jacks et al., 1955; Unger, 1995). Mulches of crop residues and other plant materials (straw, stover, leaves, corn [*Zea mays* L.] cobs, cotton [*Gossypium hirsutum* L.] gin trash, woodchips, and sawdust) are inexpensive, often readily available, and porous, thus allowing water to readily enter soils. Other porous materials used a mulch are gravel, rocks, coal, bitumen, and similar granular materials (Unger, 1995). In general, mulch effectiveness for increasing water capture increases with the amount on the soil surface (Adams, 1966; Greb, 1979; Mannering and Meyer, 1963; Moody et al., 1963; Unger, 1978, 1995).

Plastic film mulches are used extensively for agricultural crops in some countries and have, for example, increased corn grain yields in the People's Republic of China by 44 to 165% as compared with yields on unmulched areas (Ma, 1988). Their main benefit with respect to water conservation is reduced evaporation, but they do provide water capture benefits if provisions exist for water to enter the soil. In addition, they result in improved water retention by reducing weed competition for water because they effectively control weeds. Mulches of petroleum products (asphalt sprays and resins) improve water capture when untreated sites exist for water to readily infiltrate soils.

Rapid channeling of water into soil is achieved by vertical mulching, which provides a slot in soil filled with crop residues (or other porous materials) that is

open to the surface. Use of vertical mulching substantially increased soil water storage (up to 41%) under some conditions (Fairbourn and Gardner, 1972, 1974; Heilman and Gonzalez, 1973; Wendt, 1973). Using a microwatershed (small ridge) between slots, treating the zone between slots with oil, or installing check dams in furrows was important for achieving maximum water capture (Unger, 1995). A variation of vertical mulching is slot mulching (mentioned previously), which has been shown to reduce runoff from frozen soil (Saxton et al., 1981).

Fallowing

In low precipitation regions such as the 17 western U.S. states, fallowing often is practiced to increase soil water storage for the succeeding crop. Haas et al. (1974a) defined summer fallowing "as a farming practice wherein no crop is grown and all plant growth is controlled by cultivation or chemicals during a season when a crop might normally be grown." Such practice forfeits production for one season or year in anticipation of at least a partial increase in production for the next crop.

Although widely used for many years, fallowing has long been a controversial practice because, with respect to water conservation, it often results in low water storage efficiencies (often <25%) (Haas et al., 1974b; Johnson and Davis, 1972; Johnson et al., 1974; Unger, 1972). This is especially the case during the second summer of the fallow period in a wheat–fallow (WF) system (Farahani et al., 1998). In addition, yields usually are not doubled, thereby not compensating for skipping a crop one year (Haas et al., 1974b). Also, the erosion potential, especially by wind, usually is greater on fallowed areas because most crop residues are destroyed where frequent tillage is used for weed control during the fallow period (Haas et al., 1974a). Winter wheat–fallow, however, is still by far the most stable and profitable cropping system in some regions as, for example, in the low precipitation region of the U.S. Inland Pacific Northwest (W.F. Schillinger, personal communication, 2008).

Low water storage efficiency with fallow has received considerable attention with respect to tillage methods and cropping systems used. For example, water storage efficiency with the WF system at several central Great Plains locations averaged 19% with shallow tillage and harrowing and 38% with fall weed control in combination with stubble-mulch tillage (Greb et al., 1974). At Bushland, storage efficiency with the WF system was 10% with one-way disk tillage and 15% with stubble-mulch tillage (Johnson and Davis, 1972). Water storage efficiencies typically are lower in southern regions (southern and central Great Plains) than in northern regions (northern Great Plains and Canadian Prairies) (Unger and Howell, 1999) because of generally higher temperatures and potential evaporation in southern regions.

As compared with the WF system that involves about 15 mo of fallow between successive crops (Fig. 1–9), the wheat–grain sorghum–fallow (WSF) system results in about 11 mo of fallow between successive crops and results in two crops in 3 yr (Fig. 1–9). For a 13-yr study under dryland conditions involving stubble-mulch tillage at Bushland, water storage efficiency was 8% with the WF system and 14% for wheat and 14% for grain sorghum with the WSF system (Unger, 1972). For a WSF study at Bushland, wheat straw was placed on Pullman clay loam at rates ranging from 0 to 12 Mg ha^{-1} at the time of wheat harvest. Tillage was not performed during the fallow period. Water storage during the period between wheat harvest and sorghum planting averaged 46% with 12 Mg ha^{-1} straw and 23%

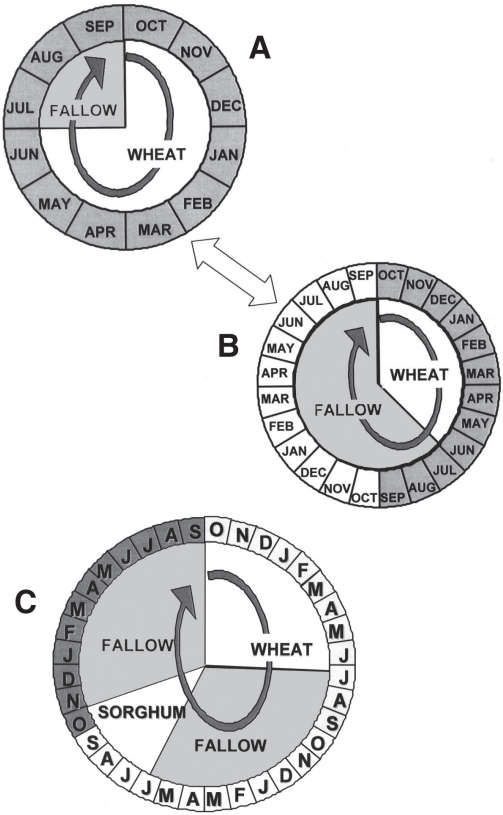

Fig. 1–9. Illustrations of (A) annual wheat, (B) wheat–fallow (one crop in 2 yr), and (C) wheat–sorghum–fallow (two crops in 3 yr) cropping systems. Illustrations provided by R.L. Baumhardt, USDA-ARS, Bushland, TX.

without straw. Grain yields of sorghum planted the spring after wheat harvest averaged 4.0 and 1.8 Mg ha^{-1} for the respective treatments (Unger, 1978).

For a WSF study at Bushland involving irrigated wheat and dryland grain sorghum, water storage efficiencies during fallow after wheat were 35% with no-tillage and 15% with disk tillage. Dryland grain sorghum after fallow yielded 3.1 Mg ha^{-1} with no-tillage and 1.9 Mg ha^{-1} with disk tillage, with the yield increase attributed mainly to the greater water storage with no-tillage (Unger and Wiese, 1979). Jones and Johnson (1983) considered alternate irrigated-dryland cropping systems appropriate for the Texas High Plains because declining water supplies are projected to limit irrigation in the region in the future.

A winter wheat–corn (or grain sorghum)–millet (*Panicum* spp.)–fallow cropping system in the central Great Plains avoids long fallow periods and results in three crops in 4 yr (Wood et al., 1991). For the northern Great Plains, spring wheat–winter wheat–fallow (two crops in 3 yr); safflower (*Carthamus tinctorius* L.)–barley (*Hordeum vulgare* L.)–winter wheat; spring wheat–corn–peas (*Pisum sativum* L.); spring wheat–winter wheat–sunflower (*Helianthus annuus* L.); spring wheat in rotation with soybean [*Glycine max* (L.) Merr.], peas, safflower, sunflower, buckwheat (*Fagopyrum esculentum* Moench), or canola (*Brassica* spp.) systems are being used (Black, 1986; Black and Tanaka, 1996; Unger and Vigil, 1998), thereby reducing the length of fallow periods. Peterson and Westfall (2004) demonstrated that

increasing cropping frequency increased the proportion of fallow months that occurred in the fall, winter, and spring months where precipitation storage efficiency was highest and dramatically decreased the proportion of fallow months that occurred in the second summer of the fallow period when no precipitation was stored as soil water.

In general, water storage efficiencies increase with decreases in length of fallow. Storage efficiency generally increases also with decreases in tillage intensity, as with stubble-mulch tillage and especially no-tillage, which result in retaining more crop residues on the surface. Using reduced tillage methods that increase soil water storage and increasing cropping intensity by growing alternative spring and summer crops (less dependence on fallow) to more efficiently use stored water are means by which producers can enhance their profitability (Havlin and Schlegel, 1997).

Other Water Capture Practices

The foregoing practices and conditions having an effect on water capture generally have been extensively researched, and many of them are widely applicable and used. The following practices generally are not widely applicable, but do provide water capture benefits so they are presented briefly.

Chain diking results in a broadcast pattern of 10-cm-deep diamond-shaped basins when used on soil loosened with a chisel, disk, or drill (Fig. 1–10). The basins have little or no effect on subsequent farming operations. The diker (Fig. 1–10), which consists of specially shaped blades welded to a large ship-anchor chain, requires little maintenance and pulling power. The basins help retain water on land, and wheat grain yields were 2.9 and 2.6 Mg ha^{-1} on diked and nondiked areas, respectively (Wiedemann and Smallacombe, 1989). Chain diking also resulted in a threefold increase in grass densities on rangeland as compared with that achieved on nondiked areas.

The surface of some soils is highly unstable, and runoff commonly occurs if the soils are not protected by residues or appropriate runoff control practices. Runoff under field conditions in Israel was reduced sixfold as compared with that from untreated soil when phosphogypsum (PG) at 10 Mg ha^{-1} was applied to a ridged sandy soil (Agassi et al., 1989). When PG at 3.0 Mg ha^{-1} was applied to a clay loam, runoff was less than from untreated bare soil, but greater than with 2.2 Mg ha^{-1} of wheat straw on the surface (Benyamini and Unger, 1984).

Injecting anionic polymers (polyacrylamide [PAM] or starch copolymer solutions) into furrow-irrigation water reduced soil loss in runoff 70% when applied at 0.7 kg ha^{-1} per irrigation. The reduction was 97% when applied at 10 g m^{-3} of water. Net and lateral infiltration was increased by using the treatments, probably because of less sediment movement and surface sealing (Lentz et al., 1992; Trout et al., 1995). A combination treatment of plant residues and PAM in furrows produced greater erosion control and larger infiltration enhancements than those achieved with residues alone (Lentz and Bjorneberg, 2003). Continuously applying PAM in irrigation water, however, decreased infiltration at all concentrations evaluated on some sandy loams in California (Ajwa and Trout, 2006).

A practice similar to contour strip cropping is contour hedging. For a 6-yr study in Peru with contour hedges 4 m apart, average annual water conservation was 287 mm greater with hedges than where rice (*Oryza sativa* L.) and cowpea [*Vigna unguiculata* (L.) Walp.] were grown in rotation without hedges. Soil loss

Fig. 1–10. (Top) Chain diker. (Bottom) Surface depressions from use of a chain diker.

was reduced 73 Mg ha^{-1} annually. Crop yields were not increased in part because hedgerows occupied 22% of the land. More time may be needed to realize the benefits of soil conservation under conditions of the study (Alegre and Rao, 1996). In Iowa, field-saturated hydraulic conductivity within a grass-hedge position was seven times greater than in a row position 7 m upslope from the hedge and 24 times greater that in the deposition position 0.5 m upslope from the hedge. Use of grass hedges increased infiltration relative to that with conventional row crop management (Rachman et al., 2004). In Missouri, a combination of grass barriers and vegetative filter strips decreased runoff by 34% (Blanco-Canqui et al., 2006), indicating the potential for conserving water with such practice. Strips of vetiver

grass [*Vetiveria zizanioides* (L.) Nash ex Small] that form dense barriers were also found to be highly effective for trapping sediments and conserving water (Erskine, 1992; Gallacher, 1990).

Cover crops are grown mainly to control erosion, but they can provide water conservation benefits with proper management. Water conservation benefits are derived from the surface cover that improves water infiltration. At Ceres, CA, the presence of cover crops increased the steady infiltration rate by 37 to 41% and cumulative infiltration by 20 to 101% (Folorunso et al., 1992). To achieve water conservation benefits, timely killing of cover crops is essential (Wagner-Riddle et al., 1994). With regard to soil water storage, cover crops may have positive or negative effects. Effects are positive when water capture is increased and negative when they limit water for the following crop or aggravate a wet soil condition. Cover crops generally are better suited for humid and subhumid regions, where precipitation is more reliable, than to semiarid regions, where precipitation is limited (Unger and Vigil, 1998).

Water Retention

After its capture, water must be retained in soil for subsequent use by plants. This is achieved by reducing losses due to evaporation, use by weeds, and deep percolation.

Evaporation

About 70% of the precipitation that falls on the U.S. land area is prevented from moving into storage bodies (including the soil) or streams by evaporation (Hatfield et al., 1992). Water stored in soil is also subject to evaporative losses, with losses occurring before crop establishment and during the growing season.

Soil water evaporation is a highly complex process that involves water potential gradients, soil temperature gradients, and atmospheric conditions. Water potential gradients occur between soil and the atmosphere and in soil itself. Ritchie (1972) recognized two stages of soil water evaporation, and Hillel (1998) and Lemon (1956) recognized three stages, but all agreed the rate was greatest during the first stage, with falling rates occurring in the subsequent stage(s).

Evaporation is greatest when soil is wet (high water potential) and air is dry (low humidity or vapor pressure). The soil water potential changes constantly due to use by plants, deep percolation, or the declining content as evaporation progresses, and increases due to precipitation or irrigation. When surface drying occurs, water must flow to the surface to replenish that lost by evaporation. Flow distances increase with continued evaporation, thereby resulting in increasingly slower liquid or vapor flow to the surface and lower evaporation rates. Eventually, water flow is only in the vapor phase, which results in the lowest rates. Besides changing water potential gradients in soil, water potentials of air constantly change due to climatic changes (temperature, humidity, vapor pressure). Other atmospheric conditions influencing evaporation are solar radiation and windspeed (Hatfield et al., 1992), which also constantly change.

Dust Mulching

According to Widtsoe (1920), dust mulching was the most important method of reducing evaporation to retain water in a soil. Fortier (1909) clearly showed that dust mulch thickness greatly affected soil water evaporation. During 21 d at Davis, CA, evaporation from containers totaled 23% of added water from soil without

mulch and 6, 2, and 0.5% from soils covered with 76-, 152-, and 387-mm-thick dust mulches, respectively. Similar reductions in evaporation due to dust mulches also occurred at other locations in the western United States (Fortier, 1909). Whether these results influenced Widtsoe (1920) is not known, but these data showed that dust mulches reduce evaporation and thereby conserve water.

The results reported by Fortier (1909) were based on studies conducted in containers. Under field conditions, dust mulching consists of a granular or powdery soil layer usually produced by tillage at a shallow depth, but it was shown to be largely ineffective for conserving water by the early 1900s, as reported by James (1945). Although it may reduce evaporation, it has not been effective in the Great Plains where precipitation occurs mainly in summer when the potential for evaporation is greatest. Under such conditions, much of the water often evaporated before tillage could be performed to create the mulch. When tillage was performed, it exposed moist soil to the atmosphere that often resulted in soil drying to the depth of tillage. Also, tillage was needed after each significant rain to reestablish the mulch. Such frequent tillage generally resulted in bare soil that was highly susceptible to erosion (Jacks et al., 1955).

Although not effective for reducing evaporation under the above conditions, dust mulching can be effective where trafficability does not unduly delay tillage so that the water already in soil can be retained. Such conditions exist where a distinct dry season follows a distinct rainy season or where water moves to the surface from deeper in soil or from a water table (Jalota and Prihar, 1990; Papendick et al., 1973; Papendick and Miller, 1977). One such region is the Inland Pacific Northwest, where dust mulching for a winter wheat–fallow system is essential for maintaining the seed-zone water content during the dry summer months for subsequent winter wheat establishment. The region receives no precipitation in the summer months.

Other Mulches

Numerous mulching materials mentioned in the Water Capture section may also reduce evaporation. Besides the amount present, crop residue characteristics that influence evaporation are their orientation (standing, flat, or matted), which affects layer thickness and porosity; layer uniformity; reflectivity, which influences the surface radiant energy balance; and aerodynamic roughness resulting from the residues (Van Doren and Allmaras, 1978). Other factors influencing evaporation include residue type, evaporation potential, precipitation characteristics, tillage practices, and soil types (Papendick and Parr, 1989), and wind speed (Tanner and Shen, 1990).

Results of several studies under field conditions clearly illustrated the value of crop residue mulches for reducing evaporation. In Colorado, Smika (1983) measured water losses during a 35-d period without precipitation. Losses were 23 mm from bare soil, 20 mm with flattened wheat straw, 19 mm with 75% flat and 25% standing straw, and 15 mm with 50% flat and 50% standing straw. Straw was 0.46 m tall, and the amount was 4.6 Mg ha^{-1}. Wind speed needed for water loss to begin increased with increases in the amount of standing straw. The loss decreased with increased amounts standing at a given wind speed. Residue orientation (standing or flat) also influenced evaporation through its influence on soil surface temperatures (48, 42, 40, and 32°C with the respective conditions), which influenced vapor pressure of the soil water. Residue height strongly influ-

ences evaporation, especially when stem populations are <300 m^{-2}. The height effect decreases with increasing stem populations (McMaster et al., 2000).

Because height of standing residues influences evaporation, a practice that maximizes residue height after harvest of a grain crop such as winter wheat is the use of a stripper header harvesting (SHH) machine (Fig. 1–11). At Bushland, taller residues after SHH reduced mean wind speed and the potential transport of water vapor (evaporation) from wet soil. Irradiant energy at the soil surface was 12% lower under SHH than under platform header harvesting (PHH) conditions. Evaporation estimated with the Bowen ratio-energy balance method was reduced 26% with SHH as compared with PHH, but actual evaporation differences were small because of dry soil conditions during the study (Baumhardt et al., 2002).

The study by Baumhardt et al. (2002) was conducted under no-tillage conditions. No-tillage provides an "in place" mulch that retains most crop residues on the soil surface, thereby improving water capture under many conditions, as indicated in the Water Capture section. The "in place" mulch generally also provides for maximum evaporation control because of residues retained on the surface.

Crop residues for field studies usually are reported on a mass per unit area basis. When evaporation values with wheat straw, grain sorghum stover, and cotton stalks on the surface were compared on a mass basis, distinct crop-specific relationships were obtained. However, when the materials were compared on a thickness (or volume) per unit area basis, differences between the relationships were small and similar to a pooled relationship between residue level and the energy-limited potential evaporation from bare soil (Steiner, 1989). Such relationships can be incorporated into crop growth models to improve water balance prediction for different cropping systems.

Plastic films, which are probably the most commonly used mulching materials other than crop residues, are highly effective for controlling evaporation. With a 100% plastic cover on soil to prevent evaporation and rainwater infiltration, grain sorghum yielded 6.3 Mg ha^{-1} with 178 mm water use from soil. On uncovered plots that were irrigated twice, grain yield was 5.8 Mg ha^{-1}, and water use was 457 mm (Griffin et al., 1966). With 90% of the surface covered with plastic, corn grain yields averaged 4.1 Mg ha^{-1}, and water use averaged 288 mm in a 2-yr study in the northern Great Plains. Without a surface cover, yields averaged 2.4 Mg ha^{-1}, and water use averaged 282 mm (Willis et al., 1963). Clearly, plastic film mulches effectively control evaporation and improve crop production.

Plastic film mulches are not widely used for field crop production in the United States, but are widely used in some countries, and especially in the People's Republic of China. A major reason for their use is water conservation, mainly through reduced evaporation. Ma (1988) reported yield increases ranging from 44 to 165% for corn with plastic mulching as compared with yields from areas not mulched. In Shanzi Province of China, average grain yields were 4.2 Mg ha^{-1} when dryland wheat was planted in three rows in 30-cm-wide furrows separated by 30-cm-wide ridges covered with plastic film. The yields were 65% greater than that of wheat without a plastic cover. The increase was attributed to improved water conservation through both an improved water supply to plants and reduced evaporation (Yang et al., 2000). In the Loess Plateau of China, Fan et al. (2005) achieved greatest plant-available soil water when soil was partially covered with plastic during the fallow before crop planting.

Fig. 1–11. (Top) Harvesting wheat with a combine equipped with a stripper-header. (Bottom) Tall wheat stubble at left is where grain was removed with a stripper-header, and shorter stubble at right is where a cutter-header was used.

Weed Control

Weed control is essential for water conservation purposes because weeds present before crop planting use soil water that could be later used by the crop. Weeds present during a crop's growing season compete directly with it for water, space, light, and nutrients. Weed control usually is achieved by tillage alone, herbicides alone, or a combination of tillage and herbicides. Other control methods are by hand (pulling or hoeing), flame devices, or pest management techniques.

With regard to water retention, timely control is essential because weeds may daily use 5 mm of water from a soil (Wicks and Smika, 1973). When tillage is used, exposing moist soil to the atmosphere may cause losses of 5 to 8 mm for each operation (Good and Smika, 1978). Water losses due to tillage, therefore, must be balanced against water used by developing weeds, which is low in early growth stages. As a result, tillage can be delayed until weeds use as much or slightly more water than that which would be lost by evaporation. The net result of delaying tillage, therefore, is that as much or more water is retained for use by the next crop. Although tillage may immediately stop water use by existing weeds, several operations may be needed to keep weeds under control throughout the cropping period and, thereby, to conserve water (Pressland and Batianoff, 1976). As with tillage, hand-weeding immediately stops water use, but repeated weeding may be needed to achieve the greatest water conservation and crop yield benefits (Twomlow et al., 1997).

To stop water use by weeds, herbicides must enter the weeds and block their physiological activity, thereby causing them to die. Weeds in early growth stages generally are easier to control with herbicides than more mature weeds (Wiese et al., 1966). Large, more mature weeds may be especially difficult to control when stressed for water.

Most crops tolerate some herbicides that can be applied before planting or at various stages during the crop's growing season. Modifications through genetic engineering have greatly expanded the opportunity to use highly effective, quick-acting herbicides to control problem weeds without damaging the planted crops. For example, growing-season weed control is now possible through the development of glyphosate [*N*-(phosphonomethyl) glycine] resistance in cultivars of cotton, soybean, corn, canola (Moll, 1997; Padgette et al., 1995; Rasche and Gadsby, 1997), and other crops. The widespread availability of glyphosate beginning in the 1980s also greatly facilitated the adoption of conservation-tillage and no-tillage practices.

Some herbicides prevent some weed seeds from germinating and, therefore, eliminate water use by such weeds. Such herbicides, however, also may prevent seed germination of the planted crop. In such cases, some crops can be grown by using "safener-treated" seed (i.e., seed treated to prevent action of the herbicide) and, thereby, achieve effective weed control during the crop's growing season (Jones and Popham, 1997). Some herbicides may not prevent germination of seed of some weeds, which then may become a problem in the planted crop. Under such conditions, careful selection of herbicides is needed to achieve weed control without damaging the crop. Unfortunately, some weeds cannot be controlled with herbicides in some crops. Also, some weeds have become resistant to herbicides, which results in major problems where reduced or no-tillage cropping is practiced (Freebairn et al., 2006), thereby thwarting water conservation efforts.

Cover crops are not classified as weeds, but they use water. Therefore, their management with respect to water retention is important, especially in drier regions where a delay in terminating their growth may result in limited soil water retention for a following crop. As a result, cover crops generally are not recommended for use under dryland conditions, as, for example, in the southern Great Plains (Unger and Vigil, 1998). An exception may be a strip tillage system in the Southern High Plains of Texas where wheat is used as a cover crop where cotton is grown. Wheat is terminated before it has a high demand

for water. Evapotranspiration (ET) was similar for such system and a conventional tillage system, but transpiration was a greater part of ET for the strip tillage system (Lascano et al., 1994).

Deep Percolation

Deep percolation occurs when the amount of water entering a soil exceeds its storage capacity, which potentially reduces the amount available for plant use because the water moves to depths beyond the reach of plant roots. Under some conditions, it may be recovered later for irrigation from an aquifer or stream. Deep percolation most frequently occurs on deep porous soils or through preferential flow paths (worm channels, decayed root channels, etc.) on almost any soil.

To reduce the potential for deep percolation losses, crops should be grown that have growing seasons (and their greatest water requirement) corresponding with the time when the potential for percolation is greatest. Other crop management options include early planting to achieve greater root development early in the growing season, growing deep-rooting crops or crop cultivars that extract water from deep in the profile (e.g., sunflower and safflower), and using appropriate fertilization practices to encourage proper root propagation. The potential for deep percolation also can be reduced by deep tillage to enhance deeper plant rooting or to bring materials that retain more water closer to the surface, installing subsurface barriers, and increasing the soil organic matter content.

When considering early planting, the crop's optimum planting time for obtaining favorable yields must be considered. Except that growing certain crops is more profitable than growing others, little or no additional expenses should be incurred when switching to deeper-rooted crops or crop cultivars, or to those having growing seasons that coincide with the time when the deep percolation potential is greatest. This contrasts with the case for deep plowing and installing subsurface barriers for which the potential benefits relative to the cost of performing such operations must be carefully considered.

Freeman silt loam (fine-silty, mixed, superactive, mesic Aquandic Palexeralfs) in eastern Washington and northern Idaho has about a 30-cm-thick A horizon overlying a well-developed A2 horizon at the 30- to 46-cm depth. The underlying B horizon is a dense silty clay loam. Moldboard plowing the soil 90 cm deep resulted in storing 53 mm more water from precipitation in the upper 90 cm of the profile than conventional plowing. Seepage along the A2 horizon may have caused water to be lost from the conventionally plowed soil (Mech et al., 1967).

The surface horizon of Hezel soil (sandy over loamy, mixed, superactive, nonacid, mesic Xeric Torriorthents) in central Washington contains about 70% sand. Moldboard plowing the soil 1 m deep reduced the surface horizon sand content to 40 to 50%. Also, it increased the plant-available water-holding capacity in the upper 30 cm from 36 mm before plowing to 61 mm after plowing (Miller and Aarstad, 1972).

Deep sandy soils generally have high percolation rates that reduce water retention and may result in reduced crop yields. Installing asphalt barriers at about a 60-cm depth in such soils generally increased efficiency of rainfall retention and enhanced crop yields (Erickson et al., 1968; Saxena et al., 1969, 1973; Robertson et al., 1973). Another possibility for reducing deep percolation water losses on sandy soils is to mix a superabsorbent (e.g., PAM) with the soil (Bhardwaj et al., 2007).

Organic materials absorb water readily. Adding large quantities of organic materials will increase the available water storage capacity of soils and in theory should reduce deep percolation losses (Shaxson and Barber, 2003). Adding such materials to soils, however, resulted in variable effects on water retention and, therefore, on percolation losses. For sandy soils, Jamison (1953) found a high positive correlation between water retention and organic matter content. In contrast, Cisse and Vachaud (1988) found that adding organic materials had no effect on the water-holding capacity of degraded sandy soils in Senegal, but it increased plant root development, water absorption, and crop yields. Because water retention by organic materials and fine soil particles (silt and clay) is similar, adding organic materials to fine-textured soils apparently would have little or no effect on water retention. It could, however, improve soil structure and, thereby, increase root proliferation and decrease deep percolation of water. Although improved soil structure, increased root proliferation, and decreased deep percolation are possible, the amount of organic materials required is very high, and applications must be continued for many years to markedly increase soil water retention (Shaxson and Barber, 2003). Also, only the plow layer usually is affected by organic matter additions (Russell, 1988).

Crop Termination Time

Continued water use does not increase yields of grain crops such as corn, wheat, and grain sorghum after they reach physiological maturity, but may improve harvestable yield by delaying plant lodging until harvest is possible. Because yield is not increased, terminating the crop at physiological maturity would stop soil water use and, thereby, conserve some water for a following crop. Some crops such as grain sorghum and cotton have an indeterminate growing season. Where such crops are not terminated by freezing temperatures, terminating their growth immediately after harvest is an alternative method for reducing continued water use. Where second or rattoon crops are possible (e.g., grain sorghum, rice, sugarcane [*Saccharum* spp.]), water use may be less than for the first crop because limited additional plant development may be required (Unger and Howell, 1999).

Efficient Water Use

After water from precipitation has been captured and retained in soil, the amount available must be used efficiently to achieve optimum crop yields and, hence, favorable returns to the producer. Likewise, irrigation water must also be used efficiently to obtain the above results.

Efficient water use in itself usually is not the major goal of producers. Rather, their main goals usually are production level, profitability, and, to some extent, production sustainability. With these goals in mind, production systems based on water availability for crop use become an important consideration for most producers. The amount of water captured and retained, however, as mentioned in previous sections, is influenced by many factors. To achieve a yield that will be profitable to the producer is termed a threshold yield. To attain such yield, a certain amount of water is needed, and such amount under dryland (non-irrigated) conditions may influence the type of cropping system used. For example, systems with long fallow periods may be less efficient regarding precipitation use, but may increase the likelihood of achieving a threshold yield from an economic viewpoint. Fortunately, use of conservation tillage has resulted in achieving both

more efficient use of precipitation and the likelihood of acceptable economic threshold yields in many cases.

Scientists have been interested in the amount of water required for successful production of different crops for many years (Briggs and Shantz, 1914; de Wit, 1958; Tanner and Sinclair, 1983). *Water use efficiency* is a term denoting the ratio of plant production to the amount of water used. This term is appropriate for comparing different production systems in detail. However, we mainly discuss practices or options that producers can use to efficiently use water available to them.

Crop Selection

Probably the most important choice a producer of rainfed crops must make is crop (or crop cultivar) selection based on the amount and timeliness of water availability. Foremost, adequate water must be available to support crop establishment and then sustain it throughout the growing season without subjecting it to severe water stress under typical conditions (e.g., average precipitation). Unfortunately, droughts sometimes occur that thwart desired production levels of a given crop. Also, greater than anticipated precipitation sometimes provides more water than required by the crop. Selecting crops on the basis of long-term precipitation averages minimizes adverse results with the crop or crop cultivar selected.

Another important consideration regarding crop selection is crop growing season length relative to the period of adequate water availability. For relatively short periods of water availability, crops with short- or medium-length growing seasons are appropriate, whereas crops with longer growing seasons can be grown when water is available for a longer time. The goal should be to closely match available water supplies with anticipated crop needs, thereby potentially avoiding severe plant water stress or the crop not using water that is available.

A third important consideration is timeliness of adequate water availability relative to when the crop is to be grown (e.g., cool- or warm-season crop). Prevailing temperatures influence what crops can be grown in different seasons.

With irrigation, the above considerations should be applied for using water efficiently. In addition, more options regarding crop selection generally are available with irrigation. For example, with irrigation, cultivars of a given crop having a longer growing season are appropriate. Also, with irrigation, some crops can be grown that cannot be grown without irrigation under some conditions.

Irrigation Management

With respect to efficient water use, the goal for irrigation is to achieve maximum production per unit of water applied. Irrigation scheduling and amount of water to apply are important management factors that influence efficient irrigation water use. Under optimum conditions, crops would be irrigated when they need water. This is accomplished to a large degree by drip (or similar) irrigation methods in which small amounts of water are applied frequently. Under most large-scale field conditions, however, such frequent applications are not practical, and irrigations supply water to soil for later use by crops. The frequency of such irrigations may be influenced by crop water needs, water availability, soil water-holding capacity, equipment limitations, and desired production level. To achieve maximum yields, relatively frequent irrigations that maintain relatively high soil water contents are required. Achieving maximum yields, however, may not result in the most efficient water use. For some crops, use of deficit (or limited)

irrigation reduced yields, but also reduced irrigation water use, increased water use efficiency, and improved capture and use of precipitation (Unger and Howell, 1999). Successful use of deficit irrigation strategies generally requires a profile full of soil water at planting.

Irrigation scheduling is influenced by such factors as crop growth stage, crop sensitivity to water deficits, and climatic conditions (precipitation, prevailing temperatures, season of the year, etc.). In addition, a preplant irrigation may be used to increase soil water content, germinate weed seeds before crop planting, leach salts from the profile, or improve conditions for seedbed preparation. Irrigation scheduling decisions can be based on a record of precipitation, knowledge of normal evapotranspiration, reports of evapotranspiration, computer models, or direct sampling to determine the soil water status. The amount of water applied should be such that runoff or deep percolation losses are avoided or minimized. Also, preplant irrigations should be as close as possible to crop needs to avoid excessive losses due to evaporation.

In addition to irrigation scheduling and the amount of water applied, cropping system management also impacts irrigation water use efficiency. As previously mentioned, ET in the southern Great Plains was similar for cotton grown after terminated wheat that was used as a cover crop and with conventional tillage, but transpiration was a greater part of ET where the terminated wheat provided a partial residue cover on the surface (strip tillage was used for managing the wheat residues) (Lascano et al., 1994). In Kansas, corn grain yields were 8.1 and 6.4% greater with strip tillage and no-tillage, respectively, than with conventional tillage, with the yield benefits resulting from less evaporation where surface residues were present (Lamm et al., 2008). Other studies in Kansas showed the benefits of surface residues for suppressing evaporation under irrigated conditions (Klocke, 2004; Lamm and Aiken, 2007; Todd et al., 1991), thereby resulting in evaporation being a smaller part of ET for corn production (Lamm and Aiken, 2007).

Alternate Irrigated–Dryland Cropping

The WSF cropping system for which irrigated wheat is rotated with dryland sorghum (mentioned previously) is an example of alternate irrigated–dryland cropping. The goal for such systems is to grow irrigated and dryland crops under conditions where water for irrigation is limited and where dryland crops can be grown but with generally low yields. After harvesting the irrigated crop, some water from irrigations may remain in the soil. In addition, the following dryland crop benefits also from water stored during the ensuing fallow period. Because dryland crops generally deplete most soil water, some water would be stored during fallow before planting the irrigated crop, and soil conditions usually are favorable for irrigation water infiltration, thus reducing the potential for runoff.

Another example of alternate irrigated–dryland cropping is to grow the same crop alternately under irrigated and dryland conditions on the same land. For winter wheat at Bushland, average grain yields on dryland were 2.3 and 2.1 Mg ha^{-1} after irrigated wheat and for continual dryland wheat, respectively. Grain yields with irrigation were 4.4 and 4.3 Mg ha^{-1} after dryland wheat and for continual irrigated wheat, respectively. Water use efficiencies were slightly greater for alternate irrigated–dryland cropping (Unger, 1977).

Opportunity Cropping

Water availability for crop production without irrigation is highly dependent on precipitation amount and timing, especially in drier regions such as the semiarid Great Plains. Under such conditions, rather rigid cropping systems such as WF and WSF often are used. The goal for using these systems is to increase soil water storage during fallow for the next crop. Precipitation timing and amounts are highly unpredictable, and substantial amounts may occur late in the growing season or soon after a crop is harvested, thus providing little opportunity for storing additional water during the ensuing fallow period. With opportunity cropping (Fig. 1–12), an adapted crop is planted when soil water conditions become favorable, thus eliminating or greatly shortening the length of the fallow period. In the southern Great Plains, for example, short-season grain sorghum can be grown after winter wheat harvest, or winter wheat can be grown after grain sorghum harvest. Other crops evaluated for opportunity cropping at Bushland were triticale (× *Triticosecale* Wittmack), forage sorghum, pearl millet [*Pennisetum glaucum* (L.) R. Br.], oat (*Avena sativa* L.), pinto bean (*Phaseolus vulgaris* L.), fall and spring canola (*Brassica* spp.), and kenaf (*Hibiscus cannabinus* L.) (Unger, 2001). Crops considered suitable for opportunity cropping at the location were winter wheat, grain sorghum, triticale, forage sorghum, pearl millet, and oat. Because opportunity cropping increases cropping intensity relative to fixed systems, precipitation is used more efficiently than with systems involving long fallow periods. Nielsen et al. (2006) showed a 45% increase in economic precipitation use efficiency (i.e., value of crops produced) from a 5-yr study comparing opportunity cropping against set rotations that included fallow in the central Great Plains.

Fig. 1–12. Grain sorghum (foreground) and kenaf (background) being evaluated as opportunity crops.

Avoiding Long Fallow Periods

Some cropping practices, as discussed in the Water Capture section under Fallowing and under Opportunity Cropping, are aimed at avoiding long fallow periods that result in low water use efficiencies under many conditions. With these practices, crops more readily use water from precipitation when it becomes available, thus resulting in generally more efficient water use.

Atmospheric Carbon Dioxide Levels

The increasing concentration of atmospheric CO_2 has potential for affecting the water relations of crops. The concentration increased from 338 ppm in 1980 to 381 ppm in 2006 (Dlugokencky and Schnell, 2007). Studies conducted under controlled environmental conditions have shown that elevated atmospheric CO_2 levels increase water use efficiency (Allen, 1999; Allen et al., 1985). A field study was conducted in the central Great Plains during three growing seasons (1984–1987) with winter wheat (a C_3 crop) under ambient (340 ppm) and elevated CO_2 levels (485, 660, and 825 ppm) (Chaudhuri et al., 1990). Plants were grown in boxes placed in the ground. Water loss was determined by lifting and weighing the boxes. The soil was a silt loam and one-half of the boxes were maintained at a high water level (field capacity; 0.38 m^3 m^{-3}), while the other half were maintained at a low water level (one-half field capacity). Even though it is well known that CO_2 is an antitranspirant (Allen et al., 1985), the amount of water transpired increased as the CO_2 level increased because the elevated CO_2 levels increased growth and leaf area. The amount of water required to produce a gram of grain was calculated from water used and grain yield for each CO_2 level (Chaudhuri et al., 1990). The water requirement (WR), which is the reciprocal of water use efficiency, decreased as CO_2 concentration increased. Under the high water level, the WR was reduced by 29% when the CO_2 level was raised from ambient (3-yr average WR = 642 mL g^{-1}) to 825 ppm (WR = 458 mL g^{-1}). Under the low water level, the WR was reduced by 31% when the CO_2 level was raised from ambient (WR = 797 mL g^{-1}) to 825 ppm (WR = 547 mL g^{-1}). The results indicated that water use by wheat will not decrease as atmospheric CO_2 concentration increases, but that water use efficiency will increase.

Kirkham et al. (1991) determined the effect of CO_2 level on big bluestem grass (*Andropogon gerardii* Vitman) (a C_4 rangeland crop) growing on a silty clay loam kept at a high water level (field capacity; 0.38 m^3 m^{-3}) or a low water level (half field capacity). The CO_2 levels were 337 ppm (ambient) and 658 ppm, about double the ambient level. The WR was calculated by dividing leaf transpiration rate by leaf photosynthetic rate. Elevated CO_2 reduced the WR by 35% for both watering regimes. Other studies, reviewed by Allen (1999) and Allen et al. (1985) for plants such as corn, cotton, and soybean, confirm the findings that, under elevated CO_2 levels, water use efficiency will increase both for C_3 and C_4 crops.

Large increases in water use efficiency under elevated CO_2 levels do not necessarily imply any reduction in crop water requirements per unit area of land (Allen, 1999). As noted by Chaudhuri et al. (1990), water use efficiency for wheat increased under elevated CO_2 levels, but transpiration also increased because of increased plant growth and leaf area. Nevertheless, as CO_2 in the atmosphere increases, farmers should be able to achieve higher crop yields per unit land area with similar amounts of water (Allen, 1999; Robinson et al., 2007). More field

data, however, are needed for the major C_3 and C_4 crops, particularly under well-watered and water-stressed conditions (Kimball, 1983), to determine how water use efficiency will change as the atmospheric CO_2 concentration increases.

Future Challenges and Opportunities

The principles of water conservation for agriculture, namely, that water must be captured, retained, and used efficiently for producing a desirable yield, have not changed during the past 100 yr. Although much progress has been made, much water potentially available for agricultural uses is not effectively conserved in many cases. With increasing demands for water by other users and the need for increased agricultural production, it is imperative that continued efforts be made to conserve and use our water supplies effectively and more efficiently. With this in mind, we list and briefly comment on some challenges and opportunities for achieving improved water conservation for agriculture.

1. Develop techniques for reducing crop residue decomposition.

Conservation tillage and especially no-tillage result in crop residues being retained on the soil surface, thereby providing major water conservation benefits under many conditions (Fig. 1–13). Unfortunately, residues decay, thus decreasing their long-term effectiveness. With less decay, greater water conservation should be possible. Possible means for reducing residue decay include using improved harvesting equipment (e.g., using the stripper header), plant breeding to develop sturdier or decay-resistant plant stems, and applying chemicals to retard decomposition.

Fig. 1–13. Crop residues on the surface in a winter wheat–grain sorghum–fallow cropping system under dryland (nonirrigated) conditions. (Left) Standing stubble of winter wheat (the most recent crop) with stalks of the previous sorghum crop lying on the surface. (Right) Standing stalks of grain sorghum (the most recent crop) with stubble of the previous wheat crop lying on the surface.

2. Identify, select, or develop more water-efficient crops or crop cultivars.

Briggs and Shantz (1914) showed major differences in water use to produce a unit yield for different crop species and for different cultivars of a given crop. Crop or cultivar selection is used to achieve efficient water use, but improved efficiency should be possible through genetic engineering techniques, through careful selection of existing crops or cultivars, and through development of improved crops or cultivars for use in a given situation (e.g., region, climatic conditions). For example, genes have been identified that may make it possible to alter corn plants (Setter, 2006), thereby potentially making corn less susceptible to drought and improving water use efficiency for that crop.

3. Determine crop responses to increasing atmospheric CO_2 levels.

Atmospheric CO_2 levels continue to increase. Studies regarding CO_2 level have been conducted, but continued research and plant breeding are warranted to stay abreast of the effect of CO_2 levels on crop productivity and water use efficiency.

4. Develop more effective herbicides or other methods for controlling weeds.

Some herbicides are most effective at a given weed growth stage. With a wider range of effectiveness, generally better weed control should be possible. In addition, some weeds are resistant to herbicides, and improved herbicides or different control methods are needed to adequately control them. Some herbicide-tolerant crops have become available through biotechnology, which has been a major benefit with regard to weed control. This practice is desirable for other crops. Progress in these areas is needed to achieve increased water use efficiency and crop productivity.

5. Develop improved phreatophyte and brush control methods.

Phreatophytes often grow beside canals, streams, or other waterways from which they extract water that could potentially be used for crop production. Brushy plants grow on rangeland and compete with grasses for water. Effective control of such plants is needed to increase the water supply for cropland and rangeland plants.

6. Consider the impacts of ethanol and biofuel production.

Several issues concerning ethanol and biofuel production have implications regarding water conservation for agriculture. In the production process itself, 3.5 to 6 units of water are used for each unit of ethanol produced (Keeney and Muller, 2006). Where grain is used for ethanol production, a large volume of water is used to produce the crop, about 1400 kg water to produce 1 kg corn grain (Stewart and Howell, 2003). Such water requirement for corn grain production results in almost 3400 L of water needed to produce 1 L of ethanol. Where corn is produced under rainfed conditions, such water use may not be of much concern. Under irrigated conditions, especially where the water supply is limited, such water use makes the production of ethanol from corn a questionable activity.

Cellulosic biofuel production also has major implications regarding water conservation. These include crop residue removal effects on water capture (runoff and infiltration effects), water retention (evaporation control), and on the soil itself (surface protection for controlling erosion, organic matter content, structure development). Information regarding these issues is available or being developed

(National Academy of Sciences, 2007; Wilhelm et al., 2007), but readily applicable guidelines or models are needed so that producers or advisors can easily determine the amount of residues needed to avoid harmful consequences at the site under consideration. The use of alternate cellulosic biofuel crops—perennial grasses, brushy plants, fast-growing trees—could reduce the need for using crop residues to produce ethanol.

7. Increase the application of practices known to improve water conservation.

Many studies have shown the value of conservation tillage for improving water conservation and use, but the practice is not used to the extent to which it is applicable. Also, such studies have not been conducted under some conditions where it could be applicable. Additional research and demonstrations involving conservation tillage (especially no-tillage) under a wide variety of cropping systems are needed to develop information so that it can be promoted through education and extension activities to achieve greater acceptance by producers.

8. Conduct interdisciplinary, more comprehensive research.

Much research pertaining to water conservation involves a small number of variables and often is conducted by one or a few researchers. Research and development teams comprised of personnel from several disciplines (e.g., soil, crop, and weed scientists; agronomists; engineers; hydrologists; economists; environmentalists; cropping-system modelers) are needed to simultaneously study more variables and to develop widely applicable, practical, and functional integrated cropping systems. These systems should effectively capture, retain, and efficiently use water; be economically suitable for producers; and help protect the environment.

Summary

The principles of water conservation for agriculture have remained constant during the past 100 years; that is, the water must be captured, retained, and used efficiently to produce a desirable yield. Deep plowing was promoted by Shaw (1911) as the primary method for capturing water in the early 1900s. Deep plowing improves water capture in some soils, but water capture can be achieved also by various less intensive practices, including ridge tillage, stubble mulch tillage, bench terracing, furrow diking, and conservation tillage, which also provide soil conservation benefits. Conservation tillage methods, especially no-tillage, are highly effective for capturing water under many conditions because the surface residues dissipate raindrop energy, thereby minimizing soil aggregate dispersion and surface sealing and maintaining favorable conditions for water infiltration. The residues also reduce the runoff rate, thus providing more time for infiltration.

To retain the captured water, water losses due to evaporation, use by weeds, and deep percolation must be minimized. Dust (soil) mulching, as promoted by Shaw (1911) and Widtsoe (1920), reduces evaporation where a distinct dry season follows a distinct rainy season, as, for example, in the Pacific Northwest. In some other regions, however, effective evaporation control can be achieved with crop residues and other mulches to obtain satisfactory water retention. Numerous herbicides are available to control weeds, and deep percolation losses can be

minimized by using appropriate management practices and applying suitable barriers in some cases.

Efficient use of the captured and retained water is largely influenced by management practices being used, including crop selection, irrigation method, and cropping systems.

The development of herbicides; improved tillage methods, including no-tillage; improved irrigation practices; and other related activities have contributed to major advances in water conservation for agriculture during the past 100 years, but challenges and opportunities remain to improve on what has been achieved.

Acknowledgments

The authors thank Cindy Warriner with Crop & Sciences at Washington State University, Ritzville, WA, for her excellent arrangement and preparation of the photos for the book chapter.

References

Aase, J.K., F.H. Siddoway, and A.L. Black. 1976. Perennial grass barriers for wind erosion control, snow management and crop production. p. 69–78. *In* Proc. Shelterbelts on the Great Plains Symp., Denver, CO. 20–22 Apr. 1976. Journal Ser. 690. Montana Agric. Exp. Stn., Bozeman.

Adams, J.E. 1966. Influences of mulches on runoff, erosion, and soil moisture depletion. Soil Sci. Soc. Am. Proc. 30:110–114.

Agassi, M., I. Shainberg, D. Warrington, and M. Ben-Hur. 1989. Runoff and erosion control in potato fields. Soil Sci. 148:149–154.

Ajwa, H.A., and T.J. Trout. 2006. Polyacrylamide and water quality effects on infiltration in sandy loam soils. Soil Sci. Soc. Am. J. 70:643–650.

Alegre, J.C., and M.R. Rao. 1996. Soil and water conservation by contour hedging in the humid tropics of Peru. Agric. Ecosyst. Environ. 57:17–25.

Alleman, R. 1982. Ecofallow catches on in wheat country. Farm J. May, p. D-4.

Allen, L.H., Jr. 1999. Evapotranspiration responses of plants and crops to carbon dioxide and temperature. p. 37–70. *In* M.B. Kirkham (ed.) Water use in crop production. The Haworth Press, Inc., New York.

Allen, L.H., Jr., P. Jones, and J.W. Jones. 1985. Rising atmospheric CO_2 and evapotranspiration. p. 13–27. *In* Advances in evapotranspiration. Proc. Natl. Conf. on Advances in Evapotranspiration. ASAE, St. Joseph, MI.

Allen, R.R., and C.R. Fenster. 1986. Stubble-mulch equipment for soil and water conservation in the Great Plains. J. Soil Water Conserv. 41:11–16.

Allen, R.R., J.T. Musick, and A.D. Schneider. 1994. Deep plowing restrictive-layer soils to improve irrigation infiltration. ASAE Paper 94-2516. ASAE, St. Joseph, MI.

Allen, R.R., J.T. Musick, and A.D. Schneider. 1995. Residual deep plowing effects on irrigation intake for Pullman clay loam. Soil Sci. Soc. Am. J. 59:1424–1429.

Allmaras, R.R., and R.H. Dowdy. 1985. Conservation tillage systems and their adoption in the United States. Soil Tillage Res. 5:197–222.

Amemiya, M. 1977. Conservation tillage in the western Corn Belt. J. Soil Water Conserv. 32:29–36.

Armbrust, D.V., and N.H. Welch. 1966. Evaluation of Zingg conservation bench terraces on Amarillo fine sandy loam soil. J. Soil Water Conserv. 21:224–226.

Barnett, A.P. 1987. Fifty years of progress in soil and water conservation at the Southern Piedmont Conservation Research Center (SPCRC), Watkinsville, Georgia, 1937–1987. Available at ftp://anyone:spc@128.192.164.106/schomberg (verified 1 Oct. 2009).

Baumhardt, R.L., O.R. Jones, and R.C. Schwartz. 2008. Long-term effects of profile modifying deep plowing on soil properties and crop yield. Soil Sci. Soc. Am. J. 72:677–682.

Baumhardt, R.L., R.C. Schwartz, and R.W. Todd. 2002. Effects of taller wheat residue after stripper header harvest on wind run, irradiant energy interception, and evaporation. p. 386–391. *In* E. van Santen (ed.) Proc. 25th Ann. Southern Conserv. Tillage Conf. for Sustainable Agric., Auburn, AL. 24–26 June 2002. Spec. Rep. 1. Alabama Agric. Exp. Stn., Auburn.

Baumhardt, R.L., C.W. Wendt, and J.W. Keeling. 1992. Chisel tillage, furrow diking, and surface crust effects on infiltration. Soil Sci. Soc. Am. J. 56:1286–1291.

Baver, L.D. 1956. Soil physics. 3rd ed. John Wiley & Sons Inc., New York.

Bennett, H.H. 1939. Soil conservation. McGraw-Hill Book Co., New York.

Benyamini, Y., and P.W. Unger. 1984. Crust development under simulated rainfall on four soils. p. 243–244. *In* 1984 Agronomy Abstracts. ASA, CSSA, and SSSA, Madison, WI.

Bhardwaj, A.K., I. Shainberg, D. Goldstein, D.N. Warrington, and G.J. Levy. 2007. Water retention and hydraulic conductivity of cross-linked polyacrylamides in sandy soils. Soil Sci. Soc. Am. J. 71:406–412.

Bilbro, J.D., and D.W. Fryrear. 1991. Pearl millet versus gin trash mulches for increasing soil water and cotton yields in a semiarid region. J. Soil Water Conserv. 46:66–69.

Black, A.L. 1967. Stubble mulching saves soil water. Montana Farmer-Stockman 54(20):22.

Black, A.L. 1986. Resources and problems in the northern Great Plains area. p. 25–38. *In* Planning and management of water conservation systems, Proc. of a Workshop, Lincoln, NE. October 1985. USDA-SCS Midwest Natl. Tech. Ctr., Lincoln, NE.

Black, A.L., and D.L. Tanaka. 1996. A conservation tillage-cropping systems study in the northern Great Plains of the USA. p. 335–342. *In* E.A. Paul et al. (ed.) Soil organic matter in temperate agroecosystems. Lewis Publ., Boca Raton, FL.

Blanco-Canqui, H., C.J. Gantzer, and S.H. Anderson. 2006. Performance of grass barriers and filter strips under interrill and concentrated flow. J. Environ. Qual. 35:1969–1974.

Bordovsky, J.P., W.M. Lyle, R.J. Lascano, and D.R. Upchurch. 1992. Cotton irrigation management with LEPA systems. Trans. ASAE 35:879–884.

Borst, H.L., and R. Woodburn. 1942. The effect of mulching and methods of cultivation on runoff and erosion from Muskingum silt loam. Agric. Eng. 23:19–24.

Bowser, W.E., and R.R. Cairns. 1967. Some effects of deep plowing a Solonetz soil. Can. J. Soil Sci. 47:239–244.

Bradford, J.M., and R.W. Blanchar. 1977. Profile modification of a Fragiudalf to increase crop production. Soil Sci. Soc. Am. J. 41:127–131.

Briggs, L.J., and J.W. McLane. 1907. The moisture equivalent of soils. USDA Bureau of Soil Bull. 45. U.S. Gov. Print. Office, Washington, DC.

Briggs, L.J., and H.L. Shantz. 1914. Relative water requirement of plants. J. Agric. Res. 3:1–64 (plus 7 plates).

Buckingham, E. 1907. Studies of the movement of soil moisture. USDA Bureau of Soils Bull. 38. U.S. Gov. Print. Office, Washington, DC.

Burnett, E. 1969. Profile modification for improved water intake and storage. Great Plains Agric. Counc. Publ. 34. Vol. 1:59–63.

Burnett, E., G.F. Arkin, and D.L. Reddell. 1974. Deep tillage effects on crop physiological response to water deficit. Paper 74-2533. ASAE, St. Joseph, MI.

Burnett, E., and C.E. Fisher. 1956. Land leveling increases dryland cotton production. Prog. Rep. 1914. Texas Agric. Exp. Stn., College Station.

Burnett, E., and V.L. Hauser. 1967. Deep tillage and soil-plant-water relationships. p. 47–52. *In* Proc. Conf. on Tillage for Greater Crop Production. 11–12 Dec. 1967. ASAE, St. Joseph, MI.

Burnett, E., B.A. Stewart, and A.L. Black. 1985. Regional effects on soil erosion and crop productivity—Great Plains. p. 285–304. *In* R.F. Follett and B.A. Stewart (ed.) Soil erosion and crop productivity. ASA, CSSA, and SSSA, Madison, WI.

Campbell, C.A., B.G. McConkey, R.P. Zentner, F. Selles, and F.B. Dyck. 1992. Benefits of wheat stubble strips for conserving snow in southwestern Saskatchewan. J. Soil Water Conserv. 47:112–115.

Chaudhuri, U.N., M.B. Kirkham, and E.T. Kanemasu. 1990. Carbon dioxide and water level effects on yield and water use of winter wheat. Agron. J. 82:637–641.

Cisse, L., and G. Vachaud. 1988. Influence d apports de matière organique sur la culture de mil et d arachide sur un sol sableux du Nord-Sénégal. I. Bilans de consommation, production et développement racinaire. Agronomie 8:315–326.

Clark, R.N., and O.R. Jones. 1981. Furrow dams for conserving rainwater in a semiarid climate. p. 198–206. *In* J.C. Siemens (ed.) Proc. Crop Production with Conservation in the 1980s, Chicago, IL. 1–2 Dec. 1980. ASAE, St. Joseph, MI.

Cochran, V.L., S.D. Sparrow, and E.B. Sparrow. 1994. Residue effects on soil micro- and macroorganisms. p. 163–184. *In* P.W. Unger (ed.) Managing agricultural residues. Lewis Publ., Boca Raton, FL.

Cox, M.B. 1968. Conservation bench terraces in Kansas. Trans. ASAE 11:387–388.

Derpsch, R. 1998. Historical review of no-tillage cultivation of crops. JIRCAS Working Rep. 13:1–18.

de Wit, C.T. 1958. Transpiration and crop yield. Versl. Landbouwk. Onder. 64(6). Inst. of Biol. and Chem. Res. on Field Crops and Herbage, Wageningen, The Netherlands.

Dickey, E.C., C.R. Fenster, J.M. Laflen, and R.H. Mickelson. 1983. Effects of tillage on soil erosion in a wheat-fallow rotation. Trans. ASAE 26:814–820.

Dickson, R.E., B.C. Langley, and C.E. Fisher. 1940. Water and soil conservation experiments at Spur, Texas. Bull. 587. Texas Agric. Exp. Stn., College Station.

Dixon, R.M. 1966. Water infiltration responses to soil management practices. Ph.D. diss. The Univ. of Wisconsin, Madison. Diss. Abstr. 66-5903.

Dlugokencky, E.J., and R.C. Schnell. 2007. Carbon dioxide. Bull. Am. Meteorol. Soc. 88 (Supple. to No. 6):S18–S19.

Doyle, A.P. 1983. Stubble retention. Available at http://www.regional.org.au/au/roc/1983/roc198365.htm (verified 1 Oct. 2009).

Duley, F.L., and C.R. Fenster. 1961. Stubble-mulch farming methods for fallow areas. E C:54–100 Nebraska Ext. Serv., Lincoln.

Duley, F.L., and L.L. Kelly. 1939. Effect of soil type, slope, and surface conditions on intake of water. Res. Bull. 112. Agric. Exp. Stn., Univ. Nebraska, Lincoln.

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

Duley, F.L., and J.C. Russel. 1942. Effects of stubble mulching on soil erosion and runoff. Soil Sci. Soc. Am. Proc. 7:77–81.

Eck, H.V., and H.M. Taylor. 1969. Profile modification of a slowly permeable soil. Soil Sci. Soc. Am. Proc. 33:779–783.

Eigel, J.D., and I.D. Moore. 1983. Effect of rainfall energy on infiltration into bare soil. p. 188–200. *In* Advances in infiltration, Proc. Natl. Conf. on Advances in Infiltration, Chicago, IL. 12–13 Dec. 1983. ASAE, St. Joseph, MI.

Erickson, A.E., C.M. Hanson, and A.J.M. Smucker. 1968. The influence of subsurface asphalt barriers on the water properties and the productivity of sand soils. Trans. 9th Int. Congr. Soil Sci. (Adelaide, Australia) 1:331–337.

Erskine, M.J. 1992. Vetiver grass: Its potential use in soil and moisture conservation in southern Africa. S. Afr. J. Sci. 88:298–299.

Fairbourn, M.L., and H.R. Gardner. 1972. Vertical mulch effects on soil water storage. Soil Sci. Soc. Am. Proc. 36:823–827.

Fairbourn, M.L., and H.R. Gardner. 1974. Field use of microwatersheds with vertical mulch. Agron. J. 66:740–744.

Fan, T., B.A. Stewart, W.A. Payne, Y. Wang, S. Song, J. Luo, and C.A. Robinson. 2005. Supplemental irrigation and water-yield relationships for plasticulture crops in the Loess Plateau of China. Agron. J. 97:177–188.

Farahani, H.J., G.A. Peterson, and D.G. Westfall. 1998. Dryland cropping intensification: A fundamental solution to efficient use of precipitation. Adv. Agron. 64:197–223.

Fehrenbacher, J.B., J.P. Vavra, and A.L. Long. 1958. Deep tillage and deep fertilization experiments on a claypan soil. Soil Sci. Soc. Am. Proc. 22:553–557.

Fenster, C.R. 1977. Conservation tillage in the Northern Plains. J. Soil Water Conserv. 32:37–42.

Fenster, C.R., N.P. Woodruff, W.S. Chepil, and F.H. Siddoway. 1965. Performance of tillage implements in a stubble mulch system: III. Effects of tillage sequences on residues, soil cloddiness, weed control, and wheat yield. Agron. J. 57:52–55.

Finnell, H.H. 1944. Water conservation in Great Plains wheat production. Bull. 655. Texas Agric. Exp. Stn., College Station.

Fisher, C.E., and E. Burnett. 1953. Conservation and utilization of soil moisture. Bull. 767. Texas Agric. Exp. Stn., College Station.

Folorunso, O.A., D.E. Rolston, T. Prichard, and D.T. Louie. 1992. Soil surface strength and infiltration rate as affected by winter cover crops. Soil Technol. 5:189–197.

Fortier, S. 1909. Soil mulches for checking evaporation. p. 465–472. *In* 1908 Yearbook of the USDA. U.S. Gov. Print. Office, Washington, DC.

Free, G.R. 1953. Stubble-mulch tillage in New York. Soil Sci. Soc. Am. Proc. 17:165–170.

Freebairn, D.M., P.S. Cornish, W.K. Anderson, S.R. Walker, J.B. Robinson, and A.R. Beswich. 2006. Management systems in climate regions of the world—Australia. p. 837–878. *In* G.A. Peterson et al. (ed.) Dryland agriculture. 2nd ed. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.

Gallacher, R.N. 1990. The search for low-input soil and water conservation techniques. Topics Appl. Resour. Manage. 2:11–37.

Gerard, C.J., P.D. Sexton, and D.M. Conover. 1984. Effect of furrow diking, subsoiling, and slope position on crop yield. Agron. J. 76:945–950.

Gerard, C.J., P.D. Sexton, and D.M. Matus. 1983. Furrow diking for cotton production in the Rolling Plains. Prog. Rep. PR-4174. Texas Agric. Exp. Stn., College Station.

Giménez, D., C. Dirksen, R. Miedema, L.A.A.J. Eppink, and D. Schoonderbeek. 1992. Surface sealing and hydraulic conductances under varying-intensity rains. Soil Sci. Soc. Am. J. 56:234–242.

Good, L.G., and D.E. Smika. 1978. Chemical fallow for soil and water conservation in the Great Plains. J. Soil Water Conserv. 33:89–90.

Greb, B.W. 1970. Deep plowing a shallow clay layer to increase soil water storage and crop yields. PR 70-23. Colorado St. Univ. Exp. Stn., Fort Collins.

Greb, B.W. 1975. Snowfall characteristics and snowmelt storage at Akron, Colorado. p. 45–64. *In* Proc. Symp. on Snow Management in the Great Plains, Bismarck, ND. 29 July 1975. Great Plains Agric. Counc., Lincoln, NE.

Greb, B.W. 1978. Weeds and water conservation in fallow. Ecofallow Conf., Ogallala, NB. 27 Feb. 1978.

Greb, B.W. 1979. Reducing drought effects on croplands in the west-central Great Plains. USDA Info. Bull. 420. U.S. Gov. Print Office, Washington, DC.

Greb, B.W. 1980. Snowfall and its potential management in the semiarid Central Great Plains. ARM-W-18. USDA, Agric. Res. Sci. and Educ. Admin., Western Region, Oakland, CA.

Greb, B.W., and A.L. Black. 1971. Vegetative barriers and artificial fences for managing snow in the central and northern plains. p. 96–111. *In* A.O Haugen (ed.) Proc. Snow and Ice in Relation to Wildlife and Recreation Symp., Ames, IA. 11–12 Feb. 1971. Iowa Coop. Wildlife Res. Unit, Iowa St. Univ., Ames.

Greb, B.W., D.E. Smika, and A.L. Black. 1970. Effect of straw-mulch rates on soil water storage during summer fallow in the Great Plains. Soil Sci. Soc. Am. Proc. 31:556–559.

Greb, B.W., D.E. Smika, N.P. Woodruff, and C.J. Whitfield. 1974. Summer fallow in the central Great Plains. p. 51–85. *In* Summer fallow in the western United States. USDA-ARS Conserv. Res. Rep. 17. U.S. Gov. Print. Office, Washington, DC.

Griffin, R.H., II, B.J. Ott, and J.F. Stone. 1966. Effect of water management and surface applied barriers on yields and moisture utilization of grain sorghum in the southern Great Plains. Agron. J. 58:449–452.

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

Haas, H.J., W.O. Willis, and J.J. Bond. 1974a. Introduction. p. 1–11. *In* Summer fallow in the western United States. USDA-ARS Conserv. Res. Rep. 17. U.S. Gov. Print. Office, Washington, DC.

Haas, H.J., W.O. Willis, and J.J. Bond. 1974b. Summer fallow in the northern Great Plains (spring wheat). p. 12–35. *In* Summer fallow in the western United States. USDA-ARS Conserv. Res. Rep. 17. U.S. Gov. Print. Office, Washington, DC.

Harker, D.B., G.R. Webster, and R.R. Cairns. 1977. Factors contributing to crop response on a deep-plowed Solonetz soil. Can. J. Soil Sci. 57:279–287.

Harper, H.J. 1941. The effect of terraces ridges on the production of winter wheat. Soil Sci. Soc. Am. Proc. 6:474–479.

Hatfield, J.L., D.C. Reicosky, J.L. Steiner, and S.B. Verma. 1992. Evaporation in agricultural systems: Implications for natural resource issues. Un-numbered report, NCR-160. Committee on Efficient Use of Water by Vegetation in Great Plains Environments, Ames, IA.

Hauser, V.L., and M.B. Cox. 1962. Evaluation of Zingg conservation bench terrace. Agric. Eng. 43:462–467.

Hauser, V.L., and H.M. Taylor. 1963. Deep tillage of High Plains Hardland soils. Texas Agric. Prog. 9(2):7–8.

Hauser, V.L., and H.M. Taylor. 1964. Evaluation of deep-tillage treatments on a slowly permeable soil. Trans. ASAE 7:134–136, 141.

Hauser, V.L., C.E. Van Doren, and J.S. Robins. 1962. A comparison of level and graded terraces in the southern Great Plains. Trans. ASAE 5:75–77.

Hauser, V.L., and A.W. Zingg. 1959. Conservation benching. Soil and Water 8:12.

Havlin, J.L., and A.J. Schlegel. 1997. Dryland conservation technologies: Enhancing agricultural profitability and sustainability. Ann. Arid Zone 36:291–303.

Heilman, M.D., and C.L. Gonzalez. 1973. Effect of narrow trenching in Harlingen clay soil on plant growth, rooting depth, and salinity. Agron. J. 65:816–819.

Hendrickson, B.H. 1939. Another look at the contour balk method. Soil Conserv. 5(2):36–37, 40.

Hillel, D. 1998. Environmental soil physics. Academic Press, San Diego, CA.

Horton, R.E. 1933. The role of infiltration in the hydrologic cycle. Trans. 14th Ann. Meeting, Am. Geophys. Union 14:446–460.

Howell, T.A., and S.R. Evett. 2005. Pathways to effective applications. p. 84–98. *In* Proc. 2005 Central Plains Irrig. Conf., Sterling, CO. 16–17 Feb. 2005.

Huxley, P.A. 1979. Zero-tillage at Morogoro, Tanzania. p. 259–265. *In* R. Lal (ed.) Soil tillage and crop production. Int. Inst. Tropical Agric. (IITA), Ibadan, Nigeria.

Jacks, G.V., W.D. Brind, and R. Smith. 1955. Mulching. Tech. Commun. 49. Commonwealth Bureau of Soil Sci., England.

Jalota, S.K., and S.S. Prihar. 1990. Bare-soil evaporation in relation to tillage. Adv. Soil Sci. 12:187–216.

James, E. 1945. Effect of certain cultural practices on moisture conservation on a Piedmont soil. J. Am. Soc. Agron. 37:945–952.

Jamison, V.C. 1953. Changes in air-water relationships due to structural improvement of soils. Soil Sci. 76:143–151.

Janick, J. 2002. Reading soil. Available at http://www.hort.purdue.edu/newcrop/tropical/lecture_06/ (verified 1 Oct. 2009).

Johnson, W.C., and R.G. Davis. 1972. Research on stubble-mulch farming of winter wheat. USDA Conserv. Res. Rep. 16. U.S. Gov. Print. Office, Washington, DC.

Johnson, W.C., C.E. Van Doren, and E. Burnett. 1974. Summer fallow in the southern Great Plains. p. 86–109. *In* Summer fallow in the western United States. USDA-ARS Conserv. Res. Rep. 17. U.S. Gov. Print. Office, Washington, DC.

Jones, O.R. 1981. Land forming effects on dryland sorghum production in the southern Great Plains. Soil Sci. Soc. Am. J. 45:606–611.

Jones, O.R., and R.N. Clark. 1987. Effects of furrow dikes on water conservation and dryland crop yields. Soil Sci. Soc. Am. J. 51:1307–1314.

Jones, O.R., and W.C. Johnson. 1983. Cropping practices: Southern Great Plains. p. 365–385. *In* H.E. Dregne and W.O. Willis (ed.) Dryland agriculture. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.

Jones, O.R., and T.W. Popham. 1997. Cropping and tillage practices for dryland grain production in the Southern High Plains. Agron. J. 89:222–232.

Keeney, D., and M. Muller. 2006. Water use by ethanol plants: Potential challenges. Inst. for Agric. and Trade Policy, Minneapolis, MN.

Kemper, W.D., T.J. Trout, A.S. Humpherys, and M.S. Bullock. 1988. Mechanism by which surge irrigation reduces furrow infiltration rates in a silty loam soil. Trans. ASAE 31:821–829.

Kimball, B.A. 1983. Carbon dioxide and agricultural yield: An assemblage and analysis of 430 prior observations. Agron. J. 75:779–788.

Kirkham, M.B., H. He, T.P. Bolger, D.J. Lawlor, and E.T. Kanemasu. 1991. Leaf photosynthesis and water use of big bluestem under elevated carbon dioxide. Crop Sci. 31:1589–1594.

Kladivko, E.J. 1994. Residue effects on soil physical properties. p. 123–141. *In* P.W. Unger (ed.) Managing agricultural residues. Lewis Publishers, Boca Raton, FL.

Klocke, N.L. 2004. Water savings from crop residue in irrigated corn. p. 133–141. *In* Proc. Central Plains Irrigation Conf., Kearney, NE. 17–18 Feb. 2004.

Krishna, J.H., G.F. Arkin, J.R. Williams, and J.R. Mulkey. 1986. Modeling furrow dike effects on runoff and crop yields. Paper 86-2016. ASAE, St. Joseph, MI.

Kuhn, T.J., K.W. Tate, D. Cao, and M.R. George. 2007. Juniper removal may not increase overall Klamath River Basin water yields. Calif. Agric. 61(4):166–171.

Lado, M., A. Paz, and M. Ben-Hur. 2004. Organic matter and aggregate size interactions in infiltration, seal formation, and soil loss. Soil Sci. Soc. Am. J. 68:935–942.

Lamm, F.R., and R.M. Aiken. 2007. Tillage and irrigation capacity effects on corn production. Paper 072283. ASABE, St. Joseph, MI.

Lamm, F.R., R.M. Aiken, and A.A. Abou Kheira. 2008. Effects of tillage practices and deficit irrigation on corn. p. 84–100. *In* Proc. Central Plains Irrigation Conf., Greeley, CO. 19–20 Feb. 2008. CPIA, Colby, KS.

Landa, E.R., and J.R. Nimmo. 2003. The life and scientific contributions of Lyman J. Briggs. Soil Sci. Soc. Am. J. 67:681–693.

Lascano, R.J., R.L. Baumhardt, S.K. Hicks, and J.L. Heilman. 1994. Soil and plant water evaporation from strip-tilled cotton: Measurement and simulation. Agron. J. 86:987–994.

Lemon, E.R. 1956. The potentialities for decreasing soil moisture evaporation loss. Soil Sci. Soc. Am. Proc. 20:120–125.

Lentz, R.D., and D.L. Bjorneberg. 2003. Polyacrylamide and straw residue effects on irrigation furrow erosion and infiltration. J. Soil Water Conserv. 58:312–319.

Lentz, R.D., I. Shainberg, R.E. Sojka, and D.L. Carter. 1992. Preventing irrigation furrow erosion with small applications of polymers. Soil Sci. Soc. Am. J. 56:1926–1932.

Levy, S. 2003. Turbulence in the Klamath River basin. Bioscience 53:315–320.

Lewis, W.M. 1985. Weed control in reduced-tillage soybean production. p. 41–50. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

Loch, R.J. 1989. Aggregate breakdown under rain: Its measurement and interpretation. Ph.D. thesis. Univ. of New England, QLD, Australia.

Lyle, W.M., and J.P. Bordovsky. 1981. Low energy precision application (LEPA) irrigation system. Trans. ASAE 24:1241–1245.

Lyle, W.M., and J.P. Bordovsky. 1983. LEPA irrigation system evaluation. Trans. ASAE 26:776–781.

Ma, S. 1988. Advances in mulch farming in China. p. 510–511. *In* P.W. Unger et al. (ed.) Challenges in dryland agriculture, A global perspective. Proc. Int. Conf. on Dryland Farming, Amarillo/Bushland, TX. 15–19 Aug. 1988. Texas Agric. Exp. Stn., College Station.

Mahler, R.L., F.G. Bailey, S. Norris, and K.A. Loeffelman. 2003. BMPs for erosion control. Available at http://www.uidaho.edu/wq/wqbr/wqbr27.html (revised 3 Jan. 2003; verified 1 Oct. 2009).

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

Maulé, C.P., and D.S. Chanasyk. 1990. The effects of tillage upon snow cover and spring soil water. Can. Agric. Eng. 32:25–31.

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

McConkey, B.G., H. Steppuhn, and W. Nicholaichuk. 1990. Effects of fall subsoiling and snow management on water conservation and continuous spring wheat yields in southwestern Saskatchewan. Can. Agric. Eng. 32:225–234.

McConkey, B.G., D.J. Ulrich, and F.B. Dyck. 1997. Snow management and deep tillage for increasing crop yields on a rolling landscape. Can. J. Soil Sci. 77:479–486.

McMaster, G.S., R.M. Aiken, and D.C. Nielsen. 2000. Optimizing wheat harvest cutting height for harvest efficiency and soil and water conservation. Agron. J. 92:1104–1108.

McWhorter, C.G., and T.N. Jordan. 1985. Limited tillage in cotton production. p. 61–76. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

Mead, J.A., and K.Y. Chan. 1988. Effect of deep tillage and seedbed preparation on the growth and yield of wheat on a hard-setting soil. Aust. J. Exp. Agric. 28:491–498.

Mech, S.J., G.M. Horner, L.M. Cox, and E.E. Cary. 1967. Soil profile modification by backhoe mixing and deep plowing. Trans. ASAE 10:775–779.

Mickelson, R.H. 1966. Level pan construction for diverting and spreading runoff. Trans. ASAE 9:568–570.

Mickelson, R.H. 1968. Conservation bench terraces in eastern Colorado. Trans. ASAE 11:389–392.

Miller, D.E., and J.S. Aarstad. 1972. Effect of deep plowing on the physical characteristics of Hezel soil. Circulation 556. Washington Agric. Exp. Stn., Pullman.

Moll, S. 1997. Commercial experience and benefits from glyphosate tolerant crops. p. 931–946. *In* Proc. 1997 Brighton Crop Prot. Conf.—Weeds, Brighton, UK. 17–20 Nov. 1997. British Crop Prot. Counc. (now BCPC), Alton, Hampshire, UK.

Moody, J.E., J.N. Jones, Jr., and J.H. Lillard. 1963. Influence of straw-mulch on soil moisture, soil temperature, and growth of corn. Soil Sci. Soc. Am. Proc. 27:700–703.

Mukhtar, S., J.L. Baker, R. Horton, and D.C. Erbach. 1985. Soil water infiltration as affected by the use of the paraplow. Trans. ASAE 28:1811–1816.

Musick, J.T., D.A. Dusek, and A.D. Schneider. 1981. Deep tillage of irrigated Pullman clay loam—A long-term evaluation. Trans. ASAE 24:1515–1519.

Musick, J.T., F.B. Pringle, W.L. Harman, and B.A. Stewart. 1988. Long-term irrigation trends—Texas High Plains. ASAE Paper SWR 88-103. ASAE, St. Joseph, MI.

National Academy of Sciences. 2007. Water implications of biofuels production in the United States. Report in brief, October 2007. The National Academy of Sciences, Washington, DC.

Nicou, R., and J.L. Chopart. 1979. Water management methods in sandy soils of Senegal. p. 248–258. *In* R. Lal (ed.) Soil tillage and crop production. Int. Inst. Tropical Agric. (IITA), Ibadan, Nigeria.

Nielsen, D.C. 1998. Snow catch and soil water recharge in standing sunflower residue. J. Prod. Agric. 11:476–480.

Nielsen, D.C., M.F. Vigil, and J.G. Benjamin. 2006. Evaluating decision rules for dryland crop selection. *In* Annual Meetings Abstracts [CD]. ASA, CSSA, and SSSA, Madison, WI.

Padgette, S.R., K.H. Kolacz, X. Delannay, D.B. Re, B.J. LaVallee, C.N. Tinius, W.K. Rhodes, Y.I. Otero, G.F. Barry, D.A. Eichholtz, V.M. Peschke, D.L. Nida, N.B. Taylor, and G.M. Kishore. 1995. Development, identification, and characterization of a glyphosate-tolerant soybean line. Crop Sci. 35:1451–1461.

Papendick, R.I., M.J. Lindstrom, and V.L. Cochran. 1973. Soil mulch effects on seedbed temperature and water during fallow in eastern Washington. Soil Sci. Soc. Am. Proc. 37:307–314.

Papendick, R.I., and D.E. Miller. 1977. Conservation tillage in the Pacific Northwest. J. Soil Water Conserv. 32:49–56.

Papendick, R.I., and J.F. Parr. 1989. The value of crop residues for water conservation. *In* Soil, crop and water management in the Sudano-Sahelian zone. Proc. Int. Workshop, ICRISAT Sahelian Center, Niamey, Niger. 7–11 Jan. 1987. ICRISAT, Patancheru, India.

Peterson, G.A., and D.G. Westfall. 2004. Managing precipitation use in sustainable dryland agroecosystems. Ann. Appl. Biol. 144:127–138.

Philip, J.R. 1969. Theory of infiltration. Adv. Hydrosci. 5:215–290.

Pikul, J.L., D.E. Wilkins, J.K. Aase, and J.F. Zuzel. 1996. Contour ripping: A tillage strategy to improve water infiltration into frozen soil. J. Soil Water Conserv. 51:76–83.

Pikul, J.L., Jr., J.F. Zuzel, and D.E. Wilkins. 1992. Infiltration in frozen soil as affected by ripping. Trans. ASAE 35:83–90.

Pressland, A.J., and G.N. Batianoff. 1976. Soil water conservation under cultivated fallows in clay soils of south-western Queensland. Aust. J. Exp. Agric. Anim. Husb. 16:564–569.

Rachman, A., S.H. Anderson, C.J. Gantzer, and A.L. Thompson. 2004. Influence of stiff-stemmed grass hedge systems on infiltration. Soil Sci. Soc. Am. J. 68:2000–2006.

Rasche, E., and M. Gadsby. 1997. Glufosinate ammonium resistant crops: International commercial developments and experiences. p. 941–946. *In* Proc. 1997 Brighton Crop Prot. Conf.—Weeds, Brighton, UK. 17–20 Nov. 1997. British Crop Prot. Counc. (now BCPC), Alton, Hampshire, UK.

Reinhardt, C., and B. Ganzel. 2007. Farming in the 1930s. Available at http://www.livinghistoryfarm.org/farminginthe30s/pests_06.html (verified 1 Oct. 2009).

Richardson, C.W. 1973. Runoff, erosion, and tillage efficiency on graded-furrow and terraced watersheds. J. Soil Water Conserv. 28:162–164.

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204–1213.

Robertson, W.K., L.C. Hammond, G.K. Saxena, and H.W. Lundy. 1973. Influence of water management through irrigation and a subsurface asphalt layer on seasonal growth and nutrient uptake of corn. Agron. J. 65:866–870.

Robinson, A.B., N.E. Robinson, and W. Soon. 2007. Environmental effects of increased atmospheric carbon dioxide. J. Am. Phys. Surg. 12:79–90.

Rothfeder, J. 2001. Every drop for sale. Penguin Putnam, Inc., New York.

Russell, E.W. 1988. Russell's soil conditions and plant growth. 11th ed. A. Wild (ed.) Longman Group, UK.

Saxena, G.K., L.C. Hammond, and H.W. Lundy. 1969. Yield and water-use efficiency of vegetables as influenced by a soil moisture barrier. Proc. Florida State Hort. Soc. 82:168–172.

Saxena, G.K., L.C. Hammond, and W.K. Robertson. 1973. Effects of subsurface asphalt layers on corn and tomato root systems. Agron. J. 65:191–194.

Saxton, K.E., D.K. McCool, and R.I. Papendick. 1981. Slot mulch for runoff and erosion control. J. Soil Water Conserv. 36:44–47.

Schillinger, W.F., and F.L. Young. 2000. Soil water use and growth of Russian thistle after wheat harvest. Agron. J. 92:167–172.

Setter, T.L. 2006. Identifying genes and their functions for drought tolerance of maize at early kernel development (abstract). *In* Annual Meetings Abstracts [CD]. ASA, CSSA, SSSA, Madison, WI.

Shaw, T. 1911. Dry land farming. The Pioneer Co., St. Paul, MN.

Shaxson, F., and R. Barber. 2003. Optimizing soil moisture for plant production. FAO Soils Bull. 79. FAO, Rome.

Shear, G.M. 1985. Introduction and history of limited tillage. p. 1–14. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

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

Soil Science Society of America. 2001. Glossary of soil science terms. SSSA, Madison, WI.

Steiner, J.L. 1989. Tillage and surface residue effects on evaporation from soil. Soil Sci. Soc. Am. J. 53:911–916.

Steiner, J.L., E.T. Kanemasu, and R.N. Clark. 1983. Spray losses and partitioning of water under a center pivot sprinkler system. Trans. ASAE 26:1128–1134.

Steppuhn, H., and J. Waddington. 1996. Conserving water and increasing alfalfa production using a tall wheatgrass windbreak system. J. Soil Water Conserv. 51:439–445.

Steppuhn, H., J. Waddington, and B.G. McConkey. 1995. Subsoiling to improve snowmelt infiltration and alfalfa yields within tall wheatgrass windbreaks. Can. Agric. Eng. 37:261–268.

Stewart, B.A. 2003. Aquifers, Ogallala. p. 43–44. *In* B.A. Stewart and T.A. Howell (ed.) Encycl. Water Sci. Marcel Dekker, New York.

Stewart, B.A., and T.A. Howell. 2003. Preface. p. xvii–xviii. *In* B.A. Stewart and T.A. Howell (ed.) Encycl. Water Sci. Marcel Dekker, New York.

Tanner, C.B., and Y. Shen. 1990. Water vapor transport through a flail-chopped corn residue. Soil Sci. Soc. Am. J. 54:945–951.

Tanner, C.B., and T.R. Sinclair. 1983. Efficient water use in crop production: Research or re-search? p. 1–27. *In* H.M. Taylor et al. (ed.) Limitations to efficient water use in crop production. ASA, CSSA, and SSSA, Madison, WI.

Taylor, S.A., and G.L. Ashcroft. 1972. Physical edaphology. W.H. Freeman and Co., San Francisco, CA.

Thomas, G.W. 1985. Managing minimum-tillage fields, fertility, and soil type. p. 211–226. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

Todd, R.W., N.L. Klocke, G.W. Hergert, and A.M. Parkhurst. 1991. Evaporation from soil influenced by crop shading, crop residue, and wetting regime. Trans. ASAE 34:461–466.

Travis, G.R., D.S. Chanasyk, and B.A. Paterson. 1990. Effects of deep plowing on soil water content and drainage of Solonetzic and associated soils. Can. Agric. Eng. 33:231–238.

Triplett, G.B., Jr. 1985. Principles of weed control for reduced-tillage corn production. p. 26–40. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

Trout, T.J., R.E. Sojka, and R.D. Lentz. 1995. Polyacrylamide effect on furrow erosion and infiltration. Trans. ASAE 38:761–765.

Tvedten, S. 2001. History of pest management—History of the development of organophosphate poisons. Available at http://www.safe2use.com/ca-ipm/01-04-27.htm (verified 1 Oct. 2009).

Twomlow, S., R. Riches, and S. Mabasa. 1997. Weeding—Its contribution to soil water conservation in semi-arid maize production. p. 185–190. *In* Proc. 1997 Brighton Crop Prot. Conf.—Weeds, Brighton, UK. 17–20 Nov. 1997. British Crop Prot. Counc. (now BCPC), Alton, Hampshire, UK.

Unger, P.W. 1972. Dryland winter wheat and grain sorghum cropping systems—Northern High Plains of Texas. Bull. 1126. Texas Agric. Exp. Stn., College Station.

Unger, P.W. 1977. Tillage effects on winter wheat production where the irrigated and dryland crops are alternated. Agron. J. 69:944–950.

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

Unger, P.W. 1979. Effects of deep tillage and profile modification on soil properties, root growth, and crop yields in the United States and Canada. Geoderma 22:275–295.

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

Unger, P.W. 1992. Infiltration of simulated rainfall: Tillage system and crop residue effects. Soil Sci. Soc. Am. J. 56:283–289.

Unger, P.W. 1993. Residual effects of soil profile modification on water infiltration, bulk density, and wheat yield. Agron. J. 85:656–659.

Unger, P.W. 1995. Role of mulches in dryland agriculture. p. 241–270. *In* U.S. Gupta (ed.) Production and improvement of crops for drylands. Oxford & IBH Publ. Co., Pvt. Ltd., New Delhi.

Unger, P.W. 2001. Alternative and opportunity dryland crops and related soil conditions in the Southern Great Plains. Agron. J. 93:216–226.

Unger, P.W. 2006. Soil and water conservation handbook: Policies, practices, conditions, and terms. The Haworth Press, Inc., New York.

Unger, P.W., and T.A. Howell. 1999. Agricultural water conservation—A global perspective. p. 1–36. *In* M.B. Kirkham (ed.) Water use in crop production. The Haworth Press, Inc., New York.

Unger, P.W., W.A. Payne, and G.A. Peterson. 2006. Water conservation and efficient use. p. 39–85. *In* G.A. Peterson et al. (ed.) Dryland agriculture. 2nd ed. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.

Unger, P.W., and M.F. Vigil. 1998. Cover crop effects on soil water relationships. J. Soil Water Conserv. 53:200–207.

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

USDA. 1908. Agricultural experiment stations of the United States, their locations, directors, and principal lines of work. p. 507–510. *In* 1907 Yearbook of the USDA. U.S. Gov. Print. Office, Washington, DC.

van Bavel, C.H.M., and R.J. Hanks. 1983. Water conservation: Principles of soil water flow, evaporation, and evapotranspiration. p. 25–34. *In* H.E. Dregne and W.O. Willis (ed.) Dryland agriculture. Agron. Monogr. 23. ASA, CSSA, and SSSA, Madison, WI.

Van Doren, D.M., Jr., and R.R. Allmaras. 1978. Effect of residue management practices on the soil physical environment, microclimate, and plant growth. p. 49–83. *In* W.R. Oschwald (ed.) Crop residue management systems. ASA Spec. Publ. 31. ASA, CSSA, and SSSA, Madison, WI.

Vyn, T.J., G. Opoku, and C.J. Swanton. 1998. Residue management and minimum tillage systems for soybeans following wheat. Agron. J. 90:131–138.

Wagner-Riddle, C., T.J. Gillespie, and C.J. Swanton. 1994. Rye cover crop management impact on soil water content, soil temperature and soybean growth. Can. J. Plant Sci. 74:485–495.

Wangemann, S.G., R.A. Kohl, and P.A. Molumeli. 2000. Infiltration and percolation influenced by antecedent soil water content and air entrapment. Trans. ASAE 43:1515–1523.

Wendt, C.W. 1973. Effects of a minimum tillage-vertical mulch concept on soil moisture and yield of grain sorghum at Lubbock, Texas, 1970–1971. Prog. Rep. PR-3152. Texas Agric. Exp. Stn., College Station.

West, T.D., D.R. Griffith, and G.C. Steinhardt. 1996. Effect of paraplowing on crop yields with no-tillage planting. J. Prod. Agric. 9:233–237.

Whitfield, C.J., C.E. Van Doren, and W. Johnson. 1949. Stubble mulch management for water conservation and erosion control on hardlands of the southern Great Plains. Bull. 711. Texas Agric. Exp. Stn., College Station.

Wicks, G.A. 1985. Weed control in conservation tillage systems– Small grains. p. 77–92. *In* A.F. Wiese (ed.) Weed control in limited tillage systems. Weed Sci. Soc. Am., Champaign, IL.

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

Wicks, G.A., D.E. Smika, and C.R. Fenster. 1972. Ecofallow—Has its time come? Paper, 1972 Nebraska Wheat Advisory Committee Meeting.

Widtsoe, J.A. 1920. Dry-farming. The MacMillan Co., New York.

Wiedemann, H.T., and B.A. Smallacombe. 1989. Chain diker—A new tool to reduce runoff. Agric. Eng. 70(5):12–15.

Wiese, A.F., T.J. Army, and J.D. Thomas. 1966. Moisture utilization by plants after herbicide treatment. Weeds 14:205–207.

Wiese, A.F., E. Burnett, and J.E. Box, Jr. 1967. Chemical fallow in dryland cropping sequences. Agron. J. 59:175–177.

Wiese, A.F., P.W. Unger, and R.R. Allen. 1985. p. 51–60. *In* A.F. Wiese (ed.) Weed control in limited-tillage systems. Weed Sci. Soc. Am., Champaign, IL.

Wilhelm, W.W., J.M.F. Johnson, D.L. Karlen, and D.T. Lightle. 2007. Corn stover to sustain soil organic carbon further constrains biomass supply. Agron. J. 99:1665–1667.

Willis, W.O., H.J. Haas, and J.S. Robbins. 1963. Moisture conservation by surface and subsurface barriers and soil configuration under semiarid conditions. Soil Sci. Soc. Am. Proc. 27:577–580.

Wockner, G., D. Freebairn, G. Hamilton, and P. Rowlands. 1996. The rough and smooth of rainfall capture in the Maranoa. Available at http://www.regional.org.au/au/asa/1996/poster/731Wockner.htm (verified 1 Oct. 2009).

Wood, C.W., D.G. Westfall, and G.A. Peterson. 1991. Soil carbon and nitrogen changes on initiation of no-till cropping systems. Soil Sci. Soc. Am. J. 55:470–476.

Yang, Q., S. Xue, R. Zhu, and W. Han. 2000. Integrated technique system of dry-farming and water-saving agriculture and mechanization in dry land of China. p. 131–136. *In* D. Niu et al. (ed.) Mechanized dryland and water-saving farming for the 21st century. Proc. China Int. Conf. on Dryland and Water-Saving Farming, Beijing, P.R. China. November 2000. China Agric. Univ. Press, Beijing.

Zingg, A.W., and V.L. Hauser. 1959. Terrace benching to save potential runoff for semiarid land. Agron. J. 51:289–292.

Zingg, A.W., and C.J. Whitfield. 1957. A summary of research experience with stubble-mulch farming. USDA Tech. Bull. 1160. U.S. Gov. Print. Office, Washington, DC.

Zuzel, J.F., and J.L. Pikul. 1987. Infiltration into a seasonally frozen agricultural soil. J. Soil Water Conserv. 42:447–450.