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Major Advances of Soil and Water Conservation in the U.S. Southern Great Plains

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The U.S. Great Plains consist of the broad expanse of prairie and steppe lands that lie east of the Rocky Mountains and cover parts of 10 states—Colorado, Kansas, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming. While the western boundary is clearly defined by the Rocky Mountain foothills, the eastern boundary occurs along the lower plains of central Texas, Oklahoma, and Kansas, where semiarid dryland production merges into rainfed farming (Baumhardt and Salinas-Garcia, 2006). This chapter will focus on the development of management practices for the combined conservation of water and soil in the southern Great Plains, which includes portions of Colorado, Kansas, Oklahoma, Texas, and New Mexico.

Soils of the southern Great Plains have integrated the effects of time, climate, and geologic factors that formed and exposed current surfaces. Trimble (1980) presented a largely nontechnical description of the geological origin and evolution of the landscape of the Great Plains. Most soils formed from a loess mantle covering the plains after aeolian deposition during the Quaternary period, except where erosion exposed earlier strata including Pliocene alluvial materials along rivers and Permian age residuum on the low or rolling plains (Cronin, 1964). The ~8 million ha of aeolian soils are typically very deep and nearly level Mollisols and Alfisols, featuring mixed high-charge (superactive) clay mineralogy, horizons of accumulated clay and calcium carbonates, and moderate to slow permeability. Soil textures generally vary from silt loams in Kansas, to silty clays in the northern Texas Panhandle, to loamy sands of the Texas South Plains. This general progression is interrupted by exposure and weathering of sediments in the valleys of the river systems crossing the Plains, particularly in the southern Great Plains by the Arkansas River and the Canadian River running eastward and the Pecos River running southward and forming a western boundary to the most southern part of the High Plains. In addition, sandy soils formed on sand hills associated with these valleys. Exposed pre-Quater-

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nary sediments in the eastern one-third of the southern Great Plains generally produced fine-textured Alfisols and Inceptisols with variable slopes, although some coarse soils formed from eroded sandstone. Most southern Great Plains soils are located in a semiarid climate or ustic moisture regime, with mesic soil temperatures in Kansas that become thermic when moving southward into Texas and New Mexico. These soils are generally productive when water is available and are well suited for irrigation.

The Great Plains region extends from the provinces of Alberta, Manitoba, and Saskatchewan in Canada southward through the central United States to the southern part of Texas (Fig. 4–1). The annual precipitation for this area varies little from north to south, but consistently decreases from east to west. For example, precipitation ranges from ~500 mm along 100°W to ~350 mm at the eastern edge of the Rocky Mountains. Although the annual precipitation east of the 100th meridian is significantly higher, essentially all of the Great Plains receives less than 700 mm of precipitation annually. Annual potential evaporation is another principal climatic factor that governs plant ecologies and cropping systems. Evaporative demand, as determined from pan measurements, increases from about 1600 mm in the east to >2400 mm along the western boundary of the Great Plains (Farnsworth et al., 1982). Unlike precipitation, however, pan evaporation, temperature, and growing season length exhibit north–south gradients, all of them decreasing from south to north (Baumhardt and Salinas-Garcia, 2006).

Fig. 4–1. The Great Plains of the United States and Canada; the 100th meridian coincides closely with the eastern border of the Texas Panhandle (Miksinski, 1998).

Evaporative demand generally exceeds precipitation by 200 to 500%, a condition that promoted native short grass prairie ecologies, encouraged development of irrigation since prehistorical times, and engendered research that emphasized soil water management on the southern Great Plains.

Development of Irrigation in the High Plains

Before Euro-American settlement, the Great Plains were largely covered with grasses, with no trees except along streams that were few and far apart. During this prehistorical period, as later, the high evaporative demand and uncertain rainfall surely encouraged the first irrigation in the southern Great Plains, which occurred as diversions of surface waters in Kansas (Erhart, 1969) and in the Oklahoma and Texas Panhandles (Thoburn, 1926, 1931). In southern Texas, surface irrigation from canals was already well established along the Rio Grande River when Coronado explored the regions in 1540 (Hutson, 1898). Major Stephen Harriman Long led a military expedition across much of the Great Plains in 1820, and upon completion, Dr. Edwin James, botanist and geologist, reported to Secretary of War, John C. Calhoun, "In regard to this extensive section of the country, I do not hesitate in giving an opinion, that it is almost wholly unfit for cultivation and of course uninhabitable by a people depending on agriculture for their subsistence" (Thwaites, 1905). Nevertheless, early cultivated agriculture developed on the Great Plains in Ellis county, Kansas, which lies immediately east of 100°W (Fig. 4–1) and was the westernmost county when organized in 1867 (Forsythe, 1977). Limited irrigated agriculture was practiced by Hispanic farmers and sheep herders along the Canadian River in Texas near Tascosa in the 1870s (Nostrand, 1996). This was more or less the beginning of historical agriculture in the central and southern Great Plains. During the late 1870s and into the 1880s, agricultural development pushed westward across the prairies into the eastern Dakotas, Nebraska, and Kansas (Hargreaves, 1977). The dry years of the 1880s and early 1890s drove many settlers out; those that remained had largely converted to a subsistence type of mixed agriculture that included ranching. Widespread ranching was aided by the discovery that an accessible aquifer, the Ogallala or High Plains Aquifer (Fig. 4–2), underlay most of the High Plains and could be

Fig. 4–2. Map of the High Plains Aquifer (USGS, 2008).

accessed by hand dug and drilled wells pumped by windmills. After 1896, however, millions of hectares of land that had been previously considered fit only for ranching because of drought were successfully dryland farmed during a period of favorable precipitation (Norrie, 1977), thus illustrating the cyclical nature of precipitation on the Great Plains. Irrigation from wells also began in semiarid western Texas during this period, with steam or gasoline powered pumps irrigating tracts of from 2 to 400 ha, and windmills irrigating tracts of ~3 ha (Hutson, 1898). Several pumping plants were capable of delivering 10,000 L min^{-1} and irrigating hundreds of hectares (Hutson, 1898).

The potential and rationale for irrigation in the Texas Panhandle were described by Hutson (1898):

> *The Llano Estacado has been described as a great plateau having an area of about 90,000 km^2 and with an almost perfectly flat surface, which rises gradually toward the northwest. No rivers cross its surface and at only a few widely scattered localities, and for short distances, is flowing water to be found. The soil is of such character that it readily drinks in the rain which falls on it. This water, or that part of it which is not soon evaporated, percolates downward and is reached by wells of 15 to 60 meters in depth. Many of these wells are capable of furnishing a supply almost inexhaustible to ordinary means of pumping. The soil is too dry to be successfully cultivated without irrigation, and this can be practiced, if at all, only by means of water raised by pumps.*

Hutson goes on to state that no more than six locations on the Plains in the Texas Panhandle had areas irrigated by means of pumps and windmills that exceeded the size of house gardens. In addition, two ranches in valleys at the edge of the Plains were irrigating some hundreds of acres at this time. Hutson (1898) assessed the future of irrigation in the Texas Panhandle with these words, "Of the future of irrigation here in general, it may be said that there is opportunity for but the little indicated, at these widely scattered spots, but that this little will prove to be just that small amount needed for rendering practicable the utilization of the High Plains for stock raising, under conditions that will be bearable for those who have to live on these great pasture lands for the conduct of the stock industry." How surprised he would have been to see the great increase of irrigation after 1940, and, how prescient his words may come to be of the future of irrigation in the Texas Panhandle.

At the same time, interest in irrigation was increasing due to the unpredictable rainfall. Large-scale irrigation in Kansas began with diversion of the Arkansas River in the 1880s for surface irrigation (Erhart, 1969). However, problems with erratic stream flow and diversion upstream for the same purpose in eastern Colorado slowed the expansion of irrigation. In 1945 irrigation began to rapidly increase until reaching a plateau of ~1.4 million ha in 1980, then declining to ~1.2 million ha by 2000 (Rogers and Wilson, 2000). Rapid expansion became feasible due to the availability of deep well submersible pumps, modern drilling equipment adapted from oil well drilling technology, internal combustion engines, and the expansion of electrical grids after World War II, and was further motivated by the drought of the 1950s. In the High Plains of Texas, irrigation from wells began in 1911 (U.S. Dep. of Interior, Bureau of Reclamation, 2009), but irrigated areas increased slowly until after the Dust Bowl of the 1930s. Rapid expansion in the Texas High Plains followed the pattern in Kansas, reaching 2.42

million ha in 1974, then declining to 1.59 million ha by 1989 before increasing to 1.87 million ha by 2000 (Colaizzi et al., 2008). Further north in Nebraska and west in the plains of Colorado, diversion of surface waters began in the later 1800s and continued until virtually all surface water flows had been diverted. In some cases, more water was diverted than could be reliably supplied by the river systems, a circumstance that engendered lawsuits and negotiations between the states that continue to have consequences to this day. But, as in Kansas, Oklahoma, and Texas, rapid improvements in drilling and pumping technology were instrumental in the rapid development of irrigation after World War II wherever the aquifer was available and the soil and landforms suitable for irrigation (Ganzel, 2009).

Early Farming Systems

The development of farming in the Great Plains increased dramatically during the first three decades of the 20th century, and H.W. Campbell had perhaps more influence on this than any other individual. Mr. Campbell was a native of Vermont, who homesteaded in Brown county, South Dakota, in 1879 (Hargreaves, 1977). In 1895, he began to promote a system, later named "Campbell's Soil Culture," based on his experience following five successive drought years. Initially, the system consisted of fall plowing, subsurface packing, light seeding, and frequent surface cultivation. The "subsurface packer" was constructed by a blacksmith using a series of wedge-shaped wheels on an axle. The wedges were designed to cut deep into the soil, packing it at the bottom of the cut while loosening the topsoil to form mulch. The basic principle of the Campbell system was packed subsoil covered with loose soil mulch. Although this was often referred to as dust mulching, Mr. Campbell warned that he was not advocating a dust blanket, but rather a soil mulch composed of soil lumps ranging in size from a pin head to a walnut. In his *Soil Culture Manual* (Campbell, 1907), he stated:

> *If you would secure the greatest possible benefit from the labor given over to cultivation, you should first provide yourself with some fine-toothed cultivator, so that the soil may be all thoroughly fined, leaving the surface of the firm soil beneath as near level as possible. Great care should be taken to catch your ground in proper condition when excess water has drained, and the soil, to the depth you wish to run your cultivator, is simply moist—neither very wet nor very dry. In this condition the little particles seem to readily separate, one from the other, then your stirred soil is composed of an innumerable number of little, minute lumps, forming a mulch that gives you the highest degree of protection. A mulch made when the soil is in this condition will never blow.*

Mr. Campbell was a publicist and promoter, claiming that his farming methods could overcome climatic handicaps in semiarid areas that could not be overcome as well in more humid areas. Campbell (1907) wrote:

> *It is stated that the best estimate based on experiments as to the extent of evaporation from the soil in the humid regions shows that fully fifty percent of the rain water which falls is returned to the air directly in vapor. But this is not true of the semiarid region, where a much smaller proportion is returned to the air in that way. And where there is cultivation with a special view to preventing this evaporation from the surface the evaporation is still less....The vital truth is that the so-called semiarid region is almost ideally adapted to*

best agriculture. The soil is of the right texture and capable of being handled to the best advantage.

Campbell's methods were promoted by business interests, particularly the railway companies, who were concerned with settlement of the region. Between 1903 and 1907, several nationally circulated periodicals carried accounts of his methods (Hargreaves, 1977). This was the message that invited settlers by the hundreds of thousands onto the Great Plains during the early years of the 20th century. A Dry Farming Congress was held in Denver in 1907, and this was followed by an annual congress for several years (Widstoe, 1911). At the end of the Denver congress that was attended by more than 1000 participants, the acting chairman, J.L. Donahue, a Denver banker, without advance notice, presented a resolution endorsing "the fundamental principles of soil culture as practiced by Professor Hardy W. Campbell" (Hargreaves, 1977). In subsequent congresses, Campbell's views were sharply challenged by representatives of the U.S. Department of Agriculture. They warned at the third Dry Farming Congress that "vastly more data must be gathered before anyone will be warranted in making any broad and sweeping generalizations concerning methods and systems of dry land agriculture" (Hargreaves, 1977). Campbell's influence in the organization thereafter declined sharply.

In retrospect, Mr. Campbell was neither a professor nor a scientist, but he possessed a good knowledge of water movement, capillary flow, and benefits of mulch. He conducted a number of successful demonstration farming operations in several states ranging from south of Amarillo, Texas to South Dakota. His shortcoming was, perhaps, a lack of understanding that the benefits of infiltration and producing a soil mulch of little particles critical to his system decreased sharply with declining organic matter, which resulted from the intensive and numerous tillage operations that were fundamental to his soil culture system.

During the decade of the 1930s, the southern Great Plains faced a crisis of drought and economic depression that had been preceded by favorable annual precipitation 100 mm above average, farm mechanization, and stable European demand for wheat (*Triticum aestivium* L.) (Baumhardt, 2003). The extensive dryland areas that had been successfully farmed for more than three decades became ravished by wind and drought. In 9 of the 12 yr between the years 1929 and 1940, rainfall amounts at Amarillo, TX failed to reach average, and between January 1933 and February 1936 the Amarillo weather bureau reported 192 dust storms (Nall, 1980). This era became known as the infamous Dust Bowl. The most damaged areas in the southern Great Plains were the Texas and Oklahoma panhandles, southwestern Kansas, southeastern Colorado, and northeastern New Mexico. Hugh Hammond Bennett of the Bureau of Chemistry and Soils of USDA in 1933 dispatched H.V. Geib from the erosion investigation station at Temple, TX to conduct a 34 county tour of the region and file a report. Geib reported that the most serious erosion had occurred in patches. He found very little damage in cultivated areas where wheat grew on heavy soils. However, in fields where farmers had planted row crops on silt loams or very sandy soils, Geib found that no less than 13 cm of surface material had been removed (Nall, 1980).

The Dust Bowl era ended with higher than average precipitation for the region, beginning in 1940, that stabilized crop production. Redesigned government programs encouraged diversified cropping systems with rotation sequences

that improved precipitation storage when innovative tillage practices from early research were adopted. Another severe drought period occurred from 1950 to 1956 for much of the southern Great Plains, but a rapid expansion of irrigation, improved tillage practices, and relatively good commodity prices prevented another catastrophic crisis like the Dust Bowl.

Early Research Studies: 1900–1940

Research conducted by USDA and the state experiment stations before 1900 was largely by individual investigators. One of the first efforts to conduct coordinated research programs involving federal and state scientists was on dryland agriculture (Quisenberry, 1977). A dryland experiment station was established at Hays, KS in 1901 as the first in the southern Great Plains (Office Technology Assessment, 1981). In October 1903, the USDA initiated research at the XIT Ranch at Channing, TX located about 60 km northwest of Amarillo (Nall, 1973). The XIT Ranch was formed in 1879 in the Texas High Plains on 1.2 Mha (3 million acres) of unsettled land sold by the Texas Legislature to finance a new state Capitol building. Although the focus of the ranch was cattle, ranch personnel began experimenting with crops in the 1890s. The station at Channing was short-lived because in 1905 the personnel and operations were transferred to the Amarillo Experiment Station established in 1904. In 1906, the Office of Dry Land Agriculture was established by USDA, and by 1910, 20 stations were in operation. Eventually, 30 stations were involved (Office Technology Assessment, 1981). Dryland cropping experiments were conducted at 22 locations in the Great Plains from 1903 to 1938 by USDA and state agricultural experiment stations (Fig. 4–3). Although many of these stations have been closed, several continue today. The Amarillo loca-

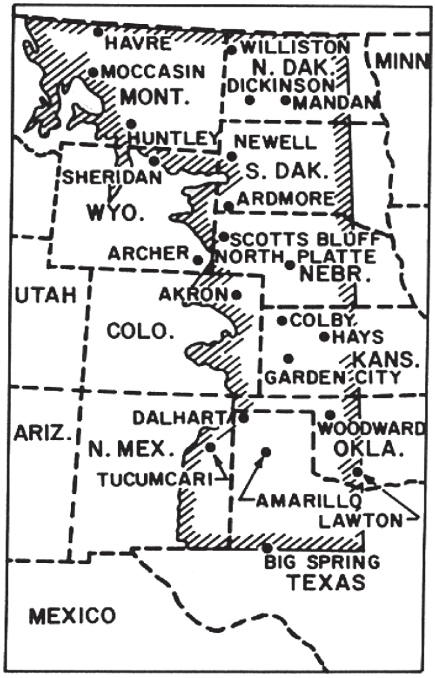

Fig. 4–3. Locations where dryland cropping experiments were conducted from 1903 to 1938 by USDA and State Agricultural Experiment Stations (Burnett et al., 1985).

tion was closed in 1938 and should not be confused with the present USDA-ARS Conservation and Production Research Laboratory at Bushland (15 km west of Amarillo) established in 1938.

Early research studies focused on determining the type of crops that would grow best in the region. Since most farmers had moved to the Great Plains from the more humid farming regions east of the Mississippi River, they brought with them their tools, seeds, and perhaps more importantly, their culture. An integral part of their culture was excessive tillage, and this, along with the widely publicized soil culture system promoted by H.W. Campbell that included frequent tillage certainly played a role in creating the conditions that led to the Dust Bowl during the drought years of the 1930s. Scientists at many of the dryland experiment stations (Fig. 4–3) warned farmers about possible consequences of frequent tillage to incorporate crop residues and refine the soil surface, which degraded the soil's natural cohesiveness and structure (Baumhardt, 2003), but high yields and favorable prices of wheat and other crops during the early years of cultivation were more important to farmers. The high yields were due to above-average rain from 1918 to 1929 (Johnson and Davis, 1972), the very favorable soil physical properties of the newly plowed lands, and the high fertility resulting from the decomposition and mineralization of the soil organic matter. Few farmers realized the high fertility was coming at the expense of declining soil organic matter, and that the declining soil organic matter was making their land less receptive for rainfall and less able to store water for subsequent crops. Moreover, farmers did not understand the effect that organic matter had on holding soil particles together in aggregates, nor the connection between aggregates and erosion, particularly by wind. The Dust Bowl was a time of reckoning, and it became clear that major changes in tillage practices had to be made if farming in the region was going to be sustainable in the future.

Research Studies: 1940–1975

Studies during and immediately following the Dust Bowl era of the 1930s focused on controlling wind erosion. The primary implements used were those invented by farmers as they struggled to protect their land resources. In 1933, Fred Hoeme, a farmer from Hooker, OK, developed a heavy-duty chisel plow. Mr. Hoeme got the idea from a piece of equipment used for road construction that was left in his field. The tool had been used to scarify the roadbed during construction; upon removal, the tool was then dragged for quite a distance through the field. Mr. Hoeme observed that the subsequent wheat crop was much better where the tool had been dragged. Thus, he began experimenting with various materials to build a chisel plow, that later became recognized by many as the "Plow that Saved the Plains." The focus of the chisel plow was to leave crop residues on the field's surface, protecting the soil from erosion and increasing water storage. An early version of the plow along with a marker was dedicated in 2000 as a Historic Landmark of Agricultural Engineering (American Society of Agricultural and Biological Engineers, 2000) at the USDA-ARS Conservation and Production Research Laboratory in Bushland, TX for permanent display. Hoeme and his sons manufactured and sold about 2000 plows from their homestead before selling the manufacturing and distribution rights to W.T. Graham in Amarillo, TX, who marketed the plow worldwide as the Graham-Hoeme plow.

The second plow developed during the Dust Bowl was by Charles Noble, an Alberta, Canada, farmer near Lethbridge. He was a leader in declaring that cultural methods had to be changed and was one of the first to condemn burying residue with dust mulch or clean summer fallow as advocated by H.W. Campbell (MacEwan, 1983). Although Mr. Noble tried for many years to develop new cultural methods for reducing tillage, he had limited success until 1935 when he got the idea for the Noble blade that became widely used throughout the Great Plains. On a trip to California, while he was still dreaming about a new type of cultivator, Noble happened to see a California farmer using a straight blade tool as an aid to cut into the subsoil to loosen his sugar beets and lift them out. The blade was heaving the soil and disturbing the plants without making much change in the general appearance of the field. Noble was instantly excited; wasting no time, he built the first prototype of the Noble blade in a friend's garage in California. The first model was a straight blade mounted on wheels; it was tested in a California orange grove. Excited with the results, Noble shortened his planned stay in California, loaded the prototype on a trailer, and returned to Canada. Prototypes of Noble blades were constructed in 1936, and shortly thereafter Mr. Noble cooperated with many scientists and organizations to evaluate the new plow (MacEwan, 1983). Later models of the Noble blade were mostly V-shaped (Fig. 4–4).

Interest in the Noble blade in the United States significantly increased in 1938 when the newly formed USDA Soil Conservation Service purchased 19 of them for testing, and the famous team of USDA scientists, F.L. Duley and J.C. Russell, then working at the University of Nebraska in Lincoln, became involved in researching the Noble blades. Mr. Noble also promoted the implement by traveling extensively throughout the Great Plains with a blade implement in tow behind his car. He traveled as far south as the Texas Panhandle (MacEwan, 1983). As with the chisel plow developed by Mr. Hoeme, the concept of the Noble Blade was to leave as much crop residue as feasible on the soil surface to prevent wind erosion and increase water storage. The term *stubble-mulching* was coined to describe these cultural practices. Although the original Noble blade design consisted of a single blade, stubble-mulching was later practiced with ganged V-shaped sweep plows (Fig. 4–5), ranging from 75 to 150 cm in width, with only about 15% of the residue being

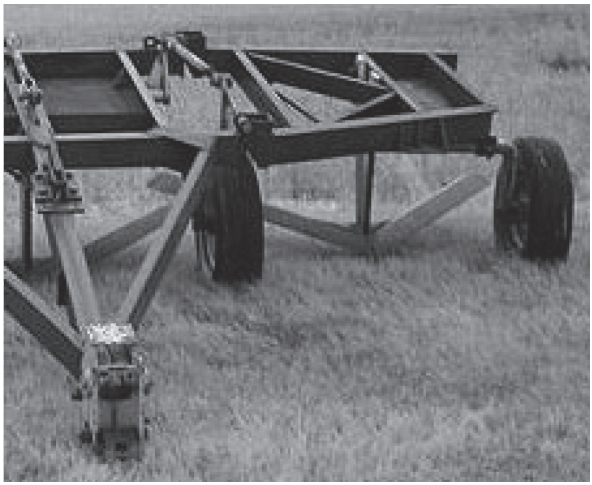

Fig. 4–4. A later version of the Noble blade first developed in 1936.

Fig. 4–5. Example of a sweep plow used in stubble-mulch tillage for weed control and retention of residues at the soil surface for soil and water conservation.

buried by a single operation (Fig. 4–5). The Noble blade and the Graham-Hoeme implements have both been recognized as Historic Agricultural Engineering Landmarks by the American Society of Agricultural and Biological Engineers.

Bushland, Texas Study

Stubble-mulching played an important role in the southern Great Plains for controlling wind erosion. Johnson et al. (1974) reported that 30 yr of study in Bushland, TX showed that stubble-mulch tillage was very effective in protecting against wind erosion and should be used routinely in place of clean tillage on summer-fallowed land. The study at Bushland was conducted from 1942 to 1970 and compared stubble-mulch tillage with soil inverting, one-way disk plowing for continuously cropped wheat (with ~3 mo between crops) and for a wheat–fallow rotation (one crop every 2 yr with ~15 mo between crops). An additional wheat–fallow treatment with delayed tillage was used in which weeds and volunteer wheat were allowed to grow after harvest until the following spring before stubble-mulch tillage.

As a general rule, a single tillage operation with a one-way plow buries about 60% of the wheat residue compared with only about 15% for a sweep plow (Steiner et al., 1994). Although stubble-mulch tillage was primarily developed to control wind erosion, Johnson et al. (1974) showed that it also conserved more water during the period between annual wheat crops. The 30-yr study showed the average amounts of plant-available soil water in the 1.5-m soil profile at time of seeding was 103 mm for stubble-mulch tillage compared with 91 mm for one-way tillage. The increased soil water also increased grain yield from 600 kg ha^{-1} to 700 kg ha^{-1}. For the wheat–fallow system, plant-available soil water at seeding was 154 mm for stubble-mulch tillage compared with 128 mm for one-way tillage, and the respective grain yields were 1070 and 950 kg ha^{-1}. Somewhat surprising was that the delayed tillage treatment with weeds and volunteer wheat growth for about 8 to 9 mo following harvest also stored 144 mm plant-available soil water at seeding time, which was only 10 mm less than the stubble-mulched plots. This treatment also yielded similarly to stubble-mulch tillage at 1040 kg ha^{-1}, which illustrates that extending the fallow period is not very efficient for increasing soil water storage.

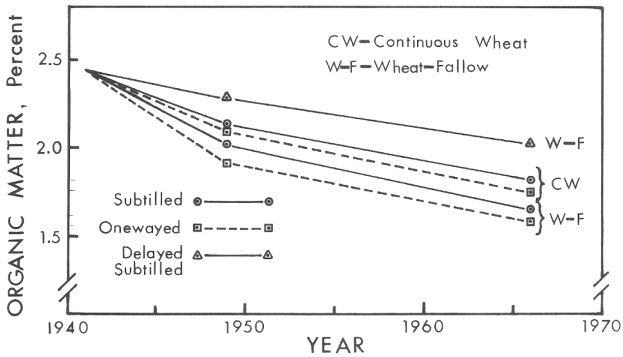

Fig. 4–6. Organic matter content, 0 to 15 cm, of tillage plots as related to cropping system (Johnson et al., 1974).

Another important finding of the long-term study reported by Johnson et al. (1974) involved the rapid decline in soil organic matter for all treatments, which was greater for one-way tillage than for stubble-mulch tillage and more for wheat–fallow than for continuous wheat (Fig. 4–6). Soil organic matter declined the least in the delayed tillage plot because of the large amounts of vegetation produced before tillage. Although the results of the delayed tillage treatment were mostly favorable, the treatment was not considered acceptable because of weed seed and uncontrolled vegetation. The decline of soil organic matter was further verified by the presence of large amounts of nitrate-nitrogen in the soil profile. At the end of the study, 210 kg ha^{-1} of nitrate N were in the 180 cm profile of the one-way tilled plots, and 131 kg ha^{-1} were in the stubble-mulched plots. More than 60% of these amounts were in the lower half of the profiles. In comparison, only 35 kg were in the delayed tillage plots, and less than 50% was in the lower half.

The wheat–fallow cropping system used in this long-term study developed from annual wheat sequences when precipitation between harvest and planting was insufficient to establish another crop (Fig. 4–7). The resulting default fallow period in a wheat–fallow sequence stabilized subsequent wheat establishment

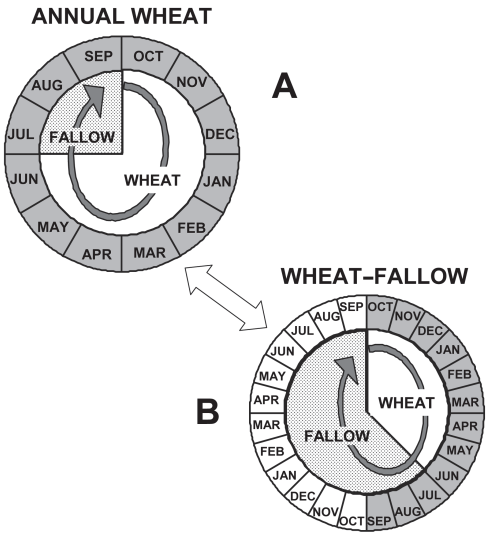

Fig. 4–7. The annual (A) wheat and (B) wheat–fallow cropping sequences diagramed as a 1- or 2-yr cycle. In both sequences, wheat is established in October (top) and harvested about 10 months later in July. Annual wheat crop establishment depends on soil water stored during the typically low precipitation months of July through September. Insufficient moisture often results in an additional 12-mo fallow period to become the wheat–fallow sequence, which stores fallow period precipitation as soil water to stabilize production of one wheat crop in 2 yr (Baumhardt and Anderson, 2006).

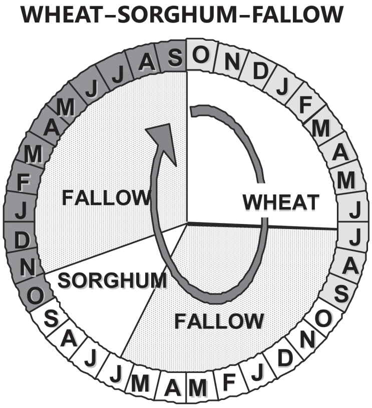

Fig. 4–8. The wheat–sorghum–fallow (WSF) rotation diagramed as a 3-yr cycle beginning with wheat establishment in October (top). Wheat is harvested 10 months later in July, and the soil is fallowed until June of the second year (11 mo) when grain sorghum is grown using soil water stored during fallow to augment summer rainfall. After sorghum harvest in November of the third year the soil is again fallowed for 10 months, when wheat is planted and the cycle repeated (Baumhardt and Anderson, 2006).

and grain yield. It has largely been replaced in the southern Great Plains, however, with a wheat–sorghum [*Sorghum bicolor* (L.) Moench]–fallow cropping system that results in two crops in 3 yr, with 11 mo between the crops (Fig. 4–8). Stewart and Robinson (1997) presented a brief comparison of these systems; it showed that nearly as much water was stored in the soil profile during 11 mo of fallow as during the almost 16 mo of fallow between crops in the wheat–fallow system.

Akron, Colorado Study

Another long-term study showing the beneficial effects of stubble-mulch tillage for controlling wind erosion, increasing soil water storage, and enhancing wheat yields was reported by Greb et al. (1979). They summarized more than 60 yr of progress in wheat production for a wheat–fallow cropping system that produced one wheat crop every 2 yr, with about 16 mo of fallow between crops (Table 4–1). The fallow efficiency (fallow period water stored in the soil divided by precipita-

Table 4–1. Progress in wheat–fallow cropping systems at Akron, CO.†

Years	Tillage	Number tillage operations	Fallow wheat storage		Wheat yield
			mm	% of precipitation	Mg ha^{-1}
1916–1930	Maximum tillage: plow, harrow (dust mulch)	7–10	102	19	1.07
1931–1945	Conventional tillage: shallow disk, rodweeder	5–7	118	24	1.16
1946–1960	Improved conventional tillage: begin stubble-mulch in 1957	4–6	137	27	1.73
1961–1975	Stubble-mulch: begin minimum tillage with herbicides in 1969	2–3	157	33	2.16
1976–1990	Minimum tillage (projected estimate): begin no-tillage in 1983	0–1	183	40	2.69

† Adapted from Greb et al. (1979).

tion and multiplied by 100) was less than 20% when frequent and intensive tillage was used but increased to approximately 30% with stubble-mulch tillage and to 40% with minimum tillage aided by herbicides for weed control. As a result of the improved water storage during the fallow period, wheat yield increased more than twofold. The positive effects accumulated with time because higher yields resulted in more crop residues, thus further enhancing soil water storage and increasing yields, creating an upward spiral. Soil physical properties are also generally improved because soil organic matter concentrations tend to increase as more crop residues are left on the soil surface and tillage is reduced.

The more than twofold increase in grain yields was due to several improved technologies. Greb (1979) attributed the credit of various technologies as follows: water conservation, 45%; improved cultivars, 30%; improved harvesting equipment, 8%; better seeding equipment, 8%; and fertilizer practices, 5%. The reason for the low impact of fertilizer was because of the long fallow period (16 mo) between crops that generally resulted in sufficient mineralization of nutrients to meet dryland crop demand. Fertilizer effects have become much more important in recent years as yields have increased and organic matter concentrations have declined to the levels that the need for fertilizers to supply adequate nutrients has greatly increased. Although Greb (1979) gave water conservation only 45% of the credit, we emphasize that without the increased water, the other technologies would have been of little or no value to a failing crop. In semiarid regions, water is typically the first limiting factor and must be addressed before other improved technologies can be of significance. The relationships shown in Fig. 4–9 illustrate how the amount of water available to the crop impacts the benefit of technologies on grain yield, but the degree of impact will be site-specific (Koohafkan and Stewart, 2008).

Before 1945, irrigation research in the United States was primarily focused on the arid western states where the federal Desert Land Act encouraged irriga-

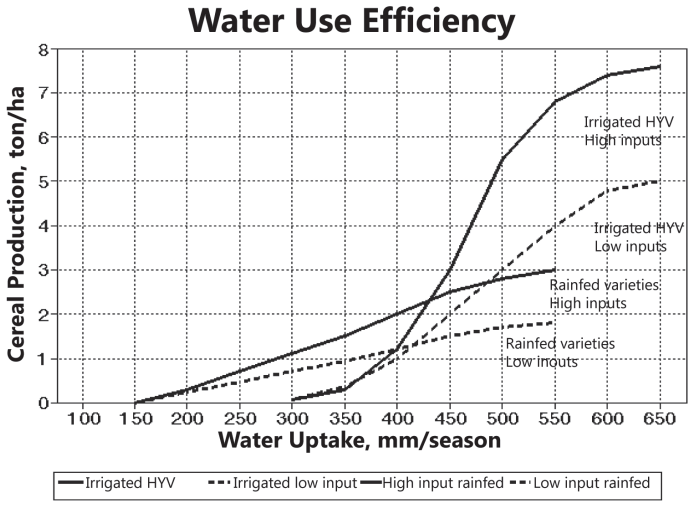

Fig. 4–9. Effects of added inputs, including high yield varieties (HYV), on the water use efficiency of cereal production (Koohafkan and Stewart, 2008).

tion as early as 1877. This was followed by the Carey Land Grant Act of 1984. This act transferred land to the western states if they provided for irrigation of those lands. For example, the Irrigation Experiment Station, which is still in existence, was established at Prosser, WA in 1919. In addition, California appointed a State Engineer to study irrigation as early as 1878. As irrigation in the Great Plains increased rapidly after 1940, research interest in the region also increased (Robins, 1959). In 1940, surface irrigation by flood, furrow, or between borders prevailed, and much of the water applied either ran off the field or percolated more deeply than plant roots could reach, leading to less availability of water for crop growth and yield production, and low overall water use efficiencies (amount of yield per unit of water applied). Since distribution was by gravity flow in mostly unlined canals and ditches, much of the water was also lost through seepage. Water logging of plants near canals was also common. Distribution in furrows was by V-notches cut into the earthen ditch or subditch walls, leading to uneven flow in the furrows. The siphon tube was invented to overcome this problem, and the first plastic siphon tube manufacturer began business in Nebraska in 1945 (Ganzel, 2009).

Siphon tubes had two problems. Setting the tubes was laborious, and the technology only worked with open canals. Research was showing how much water was lost in canals, prompting the installation of piping to eliminate seepage losses. The availability of water under pressure led to the development of gated pipe, which due to the abundance of aluminum after World War II soon became a popular alternative to siphon hoses for regulating delivery of water to furrows. The move toward pressurization of irrigation systems began in earnest at this time. Today more than 52% of the irrigated area in the United States is supplied by pressurized systems, which helps to eliminate conveyance losses.

In 1948, irrigation through sprinklers mounted on pressurized pipes in the field was already known, though not widely used in the Great Plains, when Frank Zybach in Nebraska invented the center pivot sprinkler irrigation system. The center pivot solved two problems; the labor shortage that developed during World War II and continued thereafter due to rapid urbanization of the American population, and the deep percolation losses inherent in furrow or border gravity flow irrigation systems. Adoption of center pivot systems was steady thereafter, such that today more than 70% of the irrigated area in the Southern High Plains is served by such systems (Colaizzi et al., 2008; Rogers and Wilson, 2000).

Research Studies: 1975 to Present

A second major paradigm shift in tillage began in the 1970s following the 1973 formation of the Organization of Petroleum Exporting Countries (OPEC) that sharply raised energy prices. This had a dramatic effect on agriculture because modern U.S. agriculture had been built on energy. Energy was used to plow the fields, produce fertilizer, pump water, and harvest the crops. More importantly, energy had been relatively inexpensive. From 1950 to the time that OPEC was formed, one bushel of wheat (27.3 kg) would buy about one barrel (167 L) of oil. Therefore, the cost of tillage was a small component of the cost of crop production. Although herbicides were available during much of this time period, they were generally expensive in comparison to tillage. Following the formation of OPEC, however, tillage costs increased significantly and the 1:1 wheat/oil ratio increased to as high as 20:1 in some years. This change coupled with increasing concerns

about enhancing the environment, resulted in a major shift in research, extension, and industry activities to develop and implement conservation tillage and no-tillage systems. This extended to amplify efforts to increase irrigation efficiency to reduce pumping costs and losses of water and soluble fertilizers to deep percolation. One of the results of this effort was the invention of cablegation in 1980 (Kemper et al., 1981). Cablegation used the pressure of water to move a plug down a gated pipe using a clocking mechanism to regulate the rate of movement and thus the times at which flow was turned on to each furrow. Although research continued on this method into the 1990s, and cablegation became one of several distribution options used on the smaller fields typical in Europe (de Sousa et al., 1999; Renault, 1988), by 1990 only about 100 systems had been installed in the USA (Trout and Kincaid, 1994).

Bushland, Texas Studies

Unger and Baumhardt (1999) summarized more than 40 yr of studies at Bushland, Texas, evaluating the effect of tillage on available soil water storage at grain sorghum planting (Fig. 4–10). The amounts of soil water at time of seeding after the early 1970s were dramatically more than in earlier years. The mean amount of stored soil water at seeding time from 1956 to 1969 was 102 mm compared with 173 mm from 1970 to 1997 or approximately 36 and 49% of the corresponding 10-mo fallow precipitation. Before 1970, research mainly involved clean or stubble-mulch tillage to control weeds during the fallow period between crops. Yields resulting from use of herbicides for dryland cropping were poor during that period (Wiese et al., 1960, 1967). Following the 1973 formation of OPEC, there was a major shift in research and technology transfer to practices that used less tillage and more herbicides during fallow periods. As a result, more residues remained on the soil surface as mulch; this largely accounts for the 71-mm increase in the average amount of stored soil water at time of seeding grain sorghum after 1969 (Fig. 4–10). The average 71-mm increase in stored soil water at time of seeding increased the average grain sorghum yield 1500 kg ha^{-1}, which was 21 kg ha^{-1} mm^{-1} of additional plant-available soil water at seeding. Stewart and Steiner

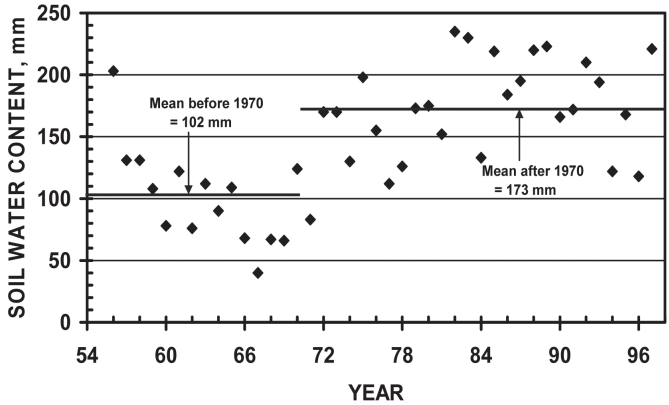

Fig. 4–10. Average annual volumetric soil water content at planting time for dryland grain sorghum in studies conducted from 1956 to 1997 at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX (Unger and Baumhardt, 1999).

(1990) summarized several studies conducted at Bushland and showed that each millimeter of additional evapotranspiration increased grain yields 15.5 kg ha^{-1} above the threshold value of 127 mm required before any grain was produced. This finding agrees closely with those of Unger and Baumhardt (1999) because it generally showed that a unit of stored plant-available soil water at time of seeding has more benefit than a unit of precipitation received during the growing season. Of course, there are exceptions to this general conclusion because some precipitation events can be particularly timely.

In response to rapidly increasing use of irrigation in the Southern High Plains, an irrigation research program was established at the USDA experiment station in Bushland, TX in 1948 to study irrigation requirements of crops and methods of water application. A sprinkler irrigation research program was begun in 1954, but did not really involve field trials in the Panhandle until 1971. Work with gated pipe began in 1964, and surge flow research began in 1982. Gravimetric and neutron moisture meter measurements were used to measure the crop soil water balance in nearly every irrigated and dryland experiment (Hauser, 1959). Bushland was involved in the trials and development of the meters by 1959. By the 1970s, research results involving tailwater retention and utilization for furrow irrigation (Schneider, 1976), limited tillage of irrigated wheat (Allen et al., 1976), and reduction of evaporative losses by retention of surface crop residues (Unger, 1976; Unger and Wiese, 1979) had been disseminated to farmers. The effect of all these methods of water conservation was to increase the yields produced per unit of water pumped.

Irrigation methods improved during the 1980s. One improvement was that alternate furrow irrigation was shown to reduce water applications but not yields of corn (*Zea mays* L.) and sorghum and to increase water use efficiency (WUE) (Musick and Dusek, 1982). This was due to the reduction in evaporative loss of water from the soil when every other furrow was wetted. Additionally, yields and water table depths continued to decline. However, limited irrigation of sorghum and sunflower (*Helianthus annuus* L.), sometimes in conjunction with dryland farming, was shown to improve the overall water use efficiency, as a result of both reduction of evaporative losses and more effective conjunctive use of rainfall (Stewart et al., 1983; Unger, 1983). Results with corn and soybean [*Glycine max* (L.) Merr.] were not positive (Eck, 1986; Eck et al., 1987).

Inefficiency in furrow irrigation was still a problem, leading to research on furrow compaction to reduce deep percolation losses (Musick et al., 1985; Musick and Pringle, 1986). During the period from 1974 through 1984, average irrigation applications declined from 404 to 347 mm yr^{-1} because of increased sprinkler irrigation, adoption of surge-flow technology with graded furrows, increases in alternative furrow irrigation and conservation tillage, decreased tailwater runoff losses, reductions in preplant irrigations, and some shifts to crops that were more successful with limited irrigation (Musick and Walker, 1987).

Musick et al. (1994) summarized 178 crop seasons of irrigated and dryland wheat data from Bushland, TX in terms of grain yield, water use, and WUE. Maximum yields required 650 to 800 mm of water, a quantity that was only available through irrigation. The WUE for irrigated production was about double that for dryland production, and the curvilinear relationship for WUE in relation to yield showed that high yields were necessary for efficient water use (Fig. 4–11). The contrast between WUE of irrigated versus dryland production was so distinct that

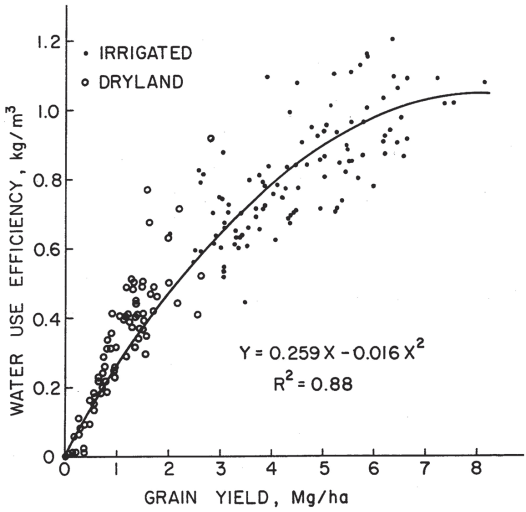

Fig. 4–11. Water use efficiency of irrigated and dryland wheat from 178 crop seasons at Bushland, TX (Musick et al., 1994).

only for a handful of seasons was the WUE of dryland production comparable to that achieved with irrigation. Tillage system studies on irrigated winter wheat–dryland sorghum rotations showed considerable improvement in both yield and WUE for no-tillage as contrasted with disk, sweep, and other tillage methods (Unger and Wiese, 1979; Unger, 1984).

In the late 1980s, a USDA-ARS research program dedicated to high accuracy crop water use determination under both irrigated and dryland production began with the installation of four large weighing lysimeters for direct crop water use measurements at Bushland (Marek et al., 1988). In subsequent years, a team led by Terry Howell determined the crop water use and WUE of fully and deficit irrigated alfalfa (*Medicago sativa* L.), corn, cotton (*Gossypium hirsutum* L.), sorghum, soybean, and winter wheat; for some the dryland water use was determined as well (Evett et al., 2000b; Howell et al., 1997b, 1998, 2004). In a partnership led by Tom Marek of Texas AgriLife (Texas A&M University), USDA-ARS cooperated with the university to establish and support networks of weather stations covering the Panhandle to provide the weather data necessary to establish daily crop water use estimates for all producers and all major crops in that region. Today, what has become the 19-station Texas High Plains Evapotranspiration Network stretches from Pecos at the southwest edge of the Plains, to Munday and Chillicothe in the Rolling Plains in the east, and to Dalhart and Perryton in the north. The network provides daily crop water use estimates for the major crops currently growing in the region, with separate values of evapotranspiration (ET) for three to four planting dates (for annual crops) and with growth stage estimates. The data are made available online, by email, and by fax. Predictions of crop ET are based on the paradigm of a daily reference ET value calculated from weather data using the Penman Monteith equation (Allen et al., 2005) multiplied by a daily crop coefficient that varies with growing degree days (Evett et al., 2000b; Howell et al., 1997b, 1998, 2004). The crop coefficients were determined by the USDA-ARS team, which also made important contributions to the American Society of Civil Engineers (ASCE) Penman Monteith standardized reference ET equations.

More efficient irrigation application methods had been studied since the beginning of sprinkler irrigation research in the 1950s. However, rapid progress did not ensue until the mid 1980s when furrow diking (creating small dikes across furrows to impede water flow) and low-energy precision application (LEPA) technology were introduced for moving irrigation systems. Stationary sprinkler systems were replaced by moving systems; by 1984, 37% of the total irrigated area was irrigated by moving systems (Musick and Walker, 1987). By the end of the 1980s, LEPA technology on moving systems became important as surface irrigated area continued to decline, particularly on more permeable soils of the region (Musick et al., 1988), and the percentage of sprinkler irrigated land rose to 44%, mostly in the northern Texas Panhandle (Musick et al., 1990). Irrigation application efficiencies increased from ~56% achieved with surface irrigation to ~82% with low-impact sprinklers in the Texas Panhandle, with similar values being recorded in Oklahoma (Musick et al., 1988). Application efficiencies achieved with LEPA systems in furrow-diked fields were consistently better than 95% (Lyle and Bordovsky, 1983). Improvements in application efficiency translated into increases in overall WUE. This is an improvement in water conservation, but not directly a reduction in water pumped, as this quote from New (1986) suggests, "center pivots improve water application efficiency enough to irrigate 20% to 25% more acreage than can be covered with furrow irrigation with the same water." As a result of continued irrigation, by 1989 the amount of water stored in the aquifer underlying the High Plains was estimated to have declined by 30% from predevelopment levels (Musick et al., 1990).

In the 1990s, irrigation research reflected the search for more efficient application methods, and the use of these to reduce evaporative losses and increase the ratio of transpiration (*T*, which reflects yields) to total water use or ET (Schneider and Howell, 1993, 1994, 1995, 1998, 1999). Much of this work focused on LEPA systems (Schneider, 2000; Schneider et al., 2000), but increasingly it compared spray, LEPA, and subsurface drip irrigation methods (Colaizzi et al., 2004; Schneider et al., 2001). Interest in drip irrigation, also known as microirrigation, began near Lubbock, TX, in the cotton industry, but drip irrigation was also studied for corn in the Texas and Kansas High Plains (Howell et al., 1997a; Lamm et al., 1995; Lamm and Trooien, 2003). Drip irrigation was shown to be more efficient and to improve *T*/ET because of the smaller wetted soil surface area (Evett et al., 1995).

Howell (2006) summarized the challenges in increasing WUE in irrigated agriculture, citing examples from the Texas High Plains. Irrigation scheduling to meet the needs of the crop without water loss to overirrigation is key, and probably as important as the choice of application technology. Although information provided by networks, like the Texas High Plains ET Network, allow farmers to make appropriate irrigation application decisions, success still depends on farmer adoption. Since the early 1990s, automatic irrigation scheduling and control systems have been the subject of research at both Bushland and Lubbock, TX (Evett et al., 1996; Wanjura et al., 1992). The systems have been applied to both drip irrigation (Evett et al., 2000a) and center pivot irrigation (Evett et al., 2006; Peters and Evett, 2008). These systems have shown the ability to incrementally improve yields and WUE over those achievable with soil water balance–based irrigation scheduling using the neutron moisture meter, which itself is superior to scheduling based on ET estimates from weather station networks. Although still not fully available in the commercial sector, some aspects of these systems are available

commercially and may be part of the next wave of improvements in overall water use efficiency in the Great Plains.

There are also factors other than water that impact grain yields, as was previously discussed (Fig. 4–9). Unger and Baumhardt (1999) showed that average annual grain sorghum yields increased from 800 kg ha^{-1} in 1939 to 3800 kg ha^{-1} in 1997. Yields increased 139% during the 1956 to 1997 time period, or about 50 kg ha^{-1} annually. The authors attributed 46 of those percentage units to the use of improved hybrids, based on results of a uniformly managed 40-yr study. The remaining 93% units were attributed primarily to soil water at time of planting and other factors. The increases in soil water at planting, as already stated, were mainly due to the adoption of improved crop residue management practices after the early 1970s. Growing-season precipitation averaged 270 mm, and total annual precipitation averaged 475 mm, but both were highly variable among years. For example, growing-season precipitation ranged from 76 mm in 1940 to 503 mm in 1960, and total precipitation ranged from 240 mm in 1970 to 828 mm in 1941, but there was no change in the mean precipitation over the long term.

Tribune, Kansas Studies

Tribune, KS is located about 375 km north of Bushland, TX in the northernmost part of the southern Great Plains. The average annual precipitation is 440 mm at Tribune compared with 475 at Bushland, but the potential evapotranspiration is significantly less at Tribune, resulting in a greater evaporation minus precipitation deficit for Bushland (Baumhardt and Salinas-Garcia, 2006). Stone and Schlegel (2006) summarized yield–water supply relationships for grain sorghum and winter wheat for studies conducted from 1974 to 2004. In the 30 years of research, various levels of tillage and/or herbicides were used during noncrop periods for weed control, including conventional, stubble-mulch (sweep) tillage with no herbicides, reduced tillage (herbicides and tillage), and no-till (herbicides exclusively). Grain sorghum yields increased an average of 22.1 kg ha^{-1} for each additional millimeter of plant-available water stored in the soil profile at time of seeding. This is very similar to the 21 kg ha^{-1} shown by Unger and Baumhardt (1999) for studies at Bushland. Likewise, Stone and Schlegel (2006) showed an increase of 16.6 kg ha^{-1} mm^{-1} of growing season water supply (i.e., plant-available soil water at seeding plus growing season precipitation) above a threshold value of 136 mm when data for all tillage systems were included. These values are very close to the 15.5 kg ha^{-1} yield increase value and the 127-mm threshold value reported by Stewart and Steiner (1990) for Bushland studies.

Stone and Schlegel (2006), however, went further in that they separated yield data from no-till, conventional till, and reduced-till treatments to identify some striking differences in grain sorghum yields associated with water supply (Fig. 4–12). For the no-tillage system, an additional millimeter of water increased grain yield 18.4 kg ha^{-1} after a threshold of 157 mm, compared with only 12.9 kg ha^{-1} after a threshold value of 102 mm for conventional and reduced tillage systems. They concluded that mulch increased the amount of precipitation stored in the soil during the fallow period, so more plant-available water was present at time of seeding. They also concluded that the mulch resulted in more efficient use of growing season precipitation.

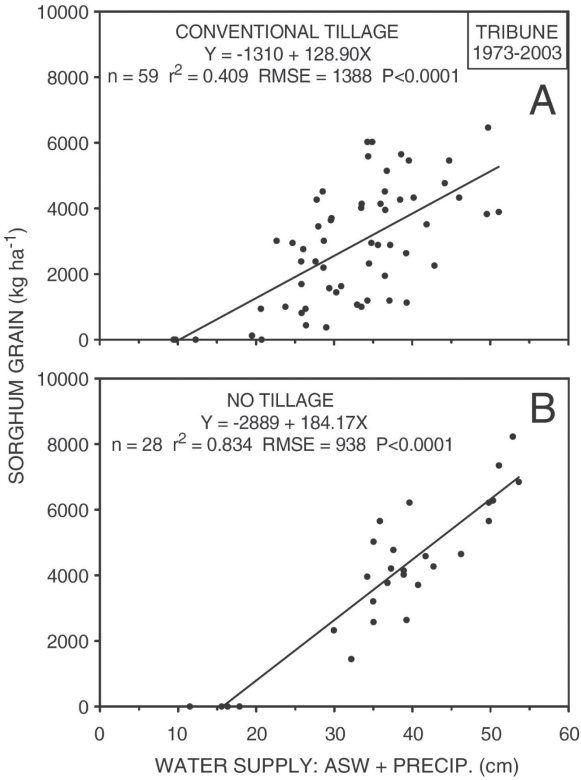

Fig. 4–12. Grain sorghum yield at Tribune, KS associated with water supply (plant-available soil water at emergence plus growing-season precipitation) for dryland conventional tillage (Section A) and for no-till (Section B) treatment groups (Stone and Schlegel, 2006).

Future Trends—Manipulating Plants to Increase Water Use Efficiency

In spite of the significant gains in storing more precipitation as soil water during fallow periods and increasing the use efficiency of growing season precipitation by leaving crop residues on the soil surface, future research must address the fact that dryland crops in the southern Great Plains are severely constrained by scarcity of growing season precipitation. Limited water during the latter growth stages becomes particularly critical for grain crops such as wheat and grain sorghum. The latter stages are the reproductive and grain-filling stages, and without water during this time, yield and quality are drastically reduced. Craufurd et al. (1993) reported that water stress during booting and flowering stages resulted in grain yield reduction of up to 85% for grain sorghum.

The studies discussed above agree that the amount of plant-available soil water at time of seeding is extremely important, and that the amount can be increased by management. An abundant supply of plant-available soil water at time of seeding can result in excellent germination and plant establishment. This is often followed by excessive vegetative growth that cannot be sustained. The challenge is to keep some of the early growing season precipitation and soil water for use during the critical grain production period. Strategies such as reduced plant populations, different spacing between rows, and skip row configurations have been tried by many researchers with mixed results. The mixed results occur

because no two growing seasons in semiarid regions are ever the same. That is, the amount, intensity, and timeliness of precipitation during the growing season are so erratic that successful cultural practices for 1 yr often fail in subsequent years. Loomis (1983) stated, in principle, that plant spacing can be varied in a way that influences the time when stored water is used. Roots can explore all of the soil volume earlier in the season with a regular spacing than with a clumped pattern. Where plants are closely spaced within rows, but widely spaced between rows, roots may reach interrow soil much later in the season. That dependence on root extension rate has the effect of spreading the use of stored water over a longer time and, for crops like grain sorghum that have developmental phases, conserving water until after anthesis.

That is the theory, although results have not always been definitive (Blum and Naveh, 1976; Bond et al., 1964). Reducing plant density is the primary management practice that scientists and farmers have relied on to conserve stored soil water for use during latter growth stages. Extension specialists and scientists have recommended planting populations as low as four plants per square meter. Even with these low plant populations, however, severe water stress occurred in most years. One explanation is that corn and particularly sorghum have the ability to produce tillers under favorable growing conditions to compensate for low plant populations and that these tillers offset the desired effect of reducing populations to conserve water. Although the formation of tillers is highly complex and affected by many factors (Bennett and Leyser, 2006; McSteen and Leyser, 2005), it is well understood that plants tiller more when they are thinly spaced and have good growing conditions. It is also well documented, under water stress conditions, that most tillers either fail to produce ears or panicles, or the number and size of grains of tiller panicles or ears are smaller (Bandaru et al., 2006; Gerik and Neely, 1987). Therefore, much of the expected benefit of a lower plant density is often negated by an increased number of tillers that utilize soil water and nutrients for vegetative growth, but contribute little or nothing to grain yield. As with practically all other findings in semiarid areas, however, there are exceptions because of the extreme variability in time, intensity, and distribution of precipitation.

Loomis (1983) stated that crop manipulations involve variations in choice of species and cultivar, timing of events, plant density, fertility status, provision for irrigation, and other factors. Loomis generalized that where soil resources are nonlimiting, uniform cropping will provide the greatest efficiency in light interception and photosynthesis. On the other hand, when soil resources are as limiting as water is in semiarid regions, nonuniform treatment of the land or the crop can be advantageous.

Relatively few scientific principles, let alone practices, are available to increase the efficient use of precipitation in semiarid areas. A maximum proportion of the evapotranspiration should be used for transpiration, with minimum losses to evaporation, drainage, and runoff. Drainage is minimal, in most cases, in semiarid regions, and runoff can be minimized or controlled by good cropping and management practices. Maximizing transpiration while minimizing evaporation during the growing season is more challenging, but usually involves establishing a full canopy as quickly and for as long as practical to minimize evaporation. This strategy works well in humid areas or irrigated conditions where water is generally not limiting. Loomis (1983) presented work from the late 1800s that applied 1 m of water to 1, 2, or 4 ha sown to various crops to determine

the best "economy-of-water." He reported that although the experiments did not detect subtle differences due to mild plant stress, deep rooting, etc., they did provide the general answer that the best water economy was obtained through practices that minimized severe stress, a result reflected in the irrigated versus dryland winter wheat study of Musick et al. (1994).

The transpiration rate decreases with an increase in humidity, and in general the humidity within a crop canopy increases with its thickness. With adequate precipitation or supplemental irrigation, narrow rows and high plant populations produce the highest yields and water use efficiencies. In the 1960s, Iowa farmers planted about 40,000 seeds ha^{-1}, and the optimum in 2007 was considered to be 85,000 (Iowa State Agronomy Extension, 2007). Since 2001, Iowa farmers have increased planting density more than 1000 plants ha^{-1} each year. Therefore, there are clearly advantages to keeping plants close together.

Mutual shading could be a factor in increasing water use efficiency. Loomis (1983) discussed the possible effects of cloud cover, screen shelters, and windbreak shelters on water use efficiency and the contributions of increased plant populations on these characteristics. Where water is limiting, however, these practices are seriously handicapped because there is not sufficient water to develop and maintain a complete canopy cover and strategies, such as low plant populations, wide row spacing, and skip row systems often expose large areas of bare soil. Not only is there more bare ground, which increases the portion of evapotranspiration attributable to evaporation, but the plants are further apart, thereby resulting in thinner canopies that allow more air to circulate, which lowers the humidity and increases the transpiration rate.

The development of approaches to manipulate plants to increase water use efficiency seems a promising area for continued research. Bandaru et al. (2006) hypothesized that growing plants in clumps would result in fewer tillers and less vegetative growth so that more soil water would be available during the grain-filling period. Results from a 3-yr study at Bushland, TX and a 1-yr study at Tribune, KS showed that planting grain sorghum in clumps of three to six plants reduced tiller formation to about one per plant, compared with about three for uniformly spaced plants. Grain yields were increased with clump planting by as much as 100% when yields were in the 1000 kg ha^{-1} range and 25 to 50% in the 2000 to 3000 kg ha^{-1} range, but when uniformly planted sorghum yields exceeded 5000 kg ha^{-1}, the clump planted sorghum yields were similar or even slightly decreased. There were also marked differences in plant architecture (Bandaru et al., 2006). That is, uniformly spaced plants produced more tillers and the leaves on both the main stalk and tillers grew outward, exposing essentially all of the leaf area to sunlight and wind. In contrast, clumped plants grew upward, with the leaves partially shading one another and reducing the effect of wind, thereby reducing water use. These results suggest that under semiarid environments where plant populations must be kept low to prevent severe water stress, growing plants in clumps rather than in uniformly spaced rows might enhance grain yields. This strategy is somewhat similar to growing plants in skip rows because skip rows also keep plants closer together than uniformly spacing the plants in all rows. In both of these strategies, however, shading of the soil surface is reduced because the plants are concentrated over a smaller area of the soil surface. Therefore, the evaporation portion of evapotranspiration will likely be higher, particularly if there are numerous small precipitation events during the growing season. This

effect could be minimized by using these strategies in a no-till cropping system, so the mulch would decrease soil evaporation during the growing season.

Summary

Soil and water conservation in the Southern High Plains are being achieved in both dryland and irrigated agricultural systems, and increasingly in combinations of these systems. The move to limit tillage and increase the retention of crop residues on the surface has not only engendered major reductions in wind erosion, but it has reduced the evaporative loss of water, making more water available for plant growth and yield formation in both dryland and irrigated systems. Irrigation application efficiencies have steadily improved with the move from surface to pressurized systems and with the ongoing improvements in reduction of evaporative losses in pressurized systems due to the introduction of LEPA and drip irrigation technologies. Irrigation scheduling methods and technologies, including automation, have reduced losses of water to runoff and deep percolation and reduced yield loss due to underirrigation, leading to overall improvement in water use efficiency. However, improvements in irrigation management, methods, and technologies can only improve the efficiency with which water is used for crop production; they cannot reduce pumping of the mostly nonrenewable water resource in the High Plains aquifer. In the end, either energy costs will make pumping noneconomical, the aquifer will be pumped until it can supply no more, or the people of the High Plains will decide to institute policies and regulations that limit pumping to sustainable levels.

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