Dryland Farming: Concept, Origin and Brief History

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1 Introduction

Dryland farming and dryland agriculture are often used synonymously. However, the raising of livestock on native vegetation can be considered dryland agriculture. In contrast, dryland farming requires conversion of a natural ecosystem to an agroecosystem, usually by tillage, and then growing introduced crops. Dryland farming is often used synonymously with rainfed farming although they can be vastly different. While both exclude irrigation, dryland farming emphasizes water conservation, sustainable crop yields, limited fertilizer and other inputs, and wind and water erosion constraints. Rainfed farming often deals with disposal of excess water and water erosion constraints, and strives for maximum crop yields using high levels of inputs (Stewart and Burnett 1987). Dryland farming occurs primarily in semiarid areas where annual precipitation is <25–50 % of the potential evapotranspiration (ET) demands (Stewart and Peterson 2015).

Dryland farming has probably been practiced since the beginning of farming. China has a recorded history of farming for more than 8000 years and people in dryland areas cultivated their land for cropping (Li 2007). Other regions in the world have long histories of dryland farming. During the seventh century, Tunis had more than a million ha of olive trees in full fruitage in the absence of irrigation with annual precipitation of about 225 mm (Shaw 1909). Koohafkan and Stewart (2008) briefly reviewed the development of dryland farming in Australia, China, Ethiopia, India, Mediterranean Regions, North America and West Africa. Drylands account for about 40 percent of the world's total land area and are home to about one-third of the population. Dryland farming is of growing importance worldwide due to the increasing demand for food and fiber. This chapter, however, is mostly limited to the

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development and practice of dryland farming in North America since its beginning in the latter half of the nineteenth century.

2 Dryland Farming in North America

Even though the American Indians began farming on the North American continent approximately 7000 years ago and in the southwest United States more than 4000 years ago (Hurt 2003), modern dryland farming originated in the middle of nineteenth century. In 1847, Brigham Young, an American leader in the Latter Day Saint movement, led a group of settlers from Illinois to the Great Salt Lake Valley that later became part of Utah. The early endeavors of these pioneers were devoted to the construction of irrigation systems. Widtsoe (1920) tells how some of these settlers transitioned to growing crops without irrigation and summarizes the results of early day experiments of dryland farming. Gradually, the pioneers were convinced that farming without irrigation was possible, but the small population was so busy with their small irrigated farms that no serious efforts at dryland farming were attempted during the first several years. Early day publications indicate that dry farming occurred occasionally as early as 1854 or 1855, but it was not until about 1863 that the first dryland farming of any consequence occurred in Utah. A number of Scandinavian immigrants settled in what is now Bear River City, Utah and irrigated their farms with the alkali water of Malad Creek. When the crops failed, the starving settlers plowed up sagebrush land in desperation, planted grain and awaited the results. Modest yields were obtained and dryland farming became an established practice in that part of the Great Salt Lake Valley. Major John Wesley Powell saw the ripened fields of grain in the hot, dry sand and made special mention of them in his report about arid lands in the west (Powell 1879).

While it appears certain that John A. Widtsoe was the first to write definitively about dryland farming in North America, his book “Dry Farming” (Widtsoe 1920) was not published for a decade after the books “Arid Agriculture” (Buffum 1909) and “Dry Land Farming” (Shaw 1909). Widtsoe’s book was clearly written many years earlier because the preface was dated June 1, 1910 and Shaw (1909) acknowledged that “he was indebted to the respective authors of the excellent books, “Arid Agriculture” and “Dry Farming” which were freely consulted in its preparation”. Though Buffam did not acknowledge Widtsoe in his book, he had a chapter entitled Dry Farming, which contained much of the information that Widtsoe used in coining the name Dry Farming to describe farming in areas previously considered not suitable. Widtsoe (1920) stated “dry farming, as at present understood, is the profitable production of useful crops, without irrigation, on lands that receive annually a rainfall of 20 in. (500 mm) or less. In districts of torrential rains, high winds, unfavorable distribution of the rainfall, or other water-dissipating factors, the term “dry farming” is also properly applied to farming without irrigation under an annual precipitation of 25 (625 mm) or even 30 inches (750 mm). There is no sharp demarcation between dry and humid farming.” He stressed, however, that dry farming always implies farming under a comparatively small annual rainfall. Even though he coined the term dry farming, Widtsoe (1920) said it was a misnomer. In reality, it is farming under drier conditions than those prevailing in the countries in which scientific agriculture originated. Widtsoe (1920) proposed that districts receiving less than 250 mm of annual atmospheric precipitation be designated arid, between 250 and 500 mm semiarid, between 500 and 750 mm subhumid and more than 750 mm humid. These values are commonly used by many todays. Based on those values, Widtsoe (1920) said that instead of dry farming, it would perhaps have been better to use arid farming, semiarid farming, humid farming and irrigation farming but 'dry farming' already in general use that it seemed unwise to suggest any change. Therefore, dry farming had for its purpose the reclamation, for the use of man, of vast areas of the world that had previously been considered unsuitable for growing crops.

Shaw (1909) used the term Dry Land Farming and defined it by both what it means and what it does not mean. He stated that it does not mean growing crops without water which would be absurd, but growing them with less water than would be successful without resorting to special methods of cultivation. It does not mean the growing of crops in all areas where precipitation falls. The degree of precipitation essential to growing crops is highly variable, since it is influenced by the soil and the nature of the evaporation. It does not mean growing tilled crops every year on the same land. Under some conditions, it is possible to grow only one crop in two years. It does not mean growing crops to the exclusion of livestock. Dry farming means (1) growing crops under semiarid conditions, (2) growing crops where moisture is normally deficient, (3) growing crops where moisture is temporarily deficient and (4) growing special crops by special methods. Shortage of moisture supply is the dominant thought that underlies any definition that may be framed regarding dryland farming.

Buffum (1909) wrote an early handbook for farmers and stockmen dealing with dryland farming. He titled his book "Arid Agriculture" because he felt Dry Farming was an untruth because no crop can be grown without moisture. Even though he objected to the name Dry Farming, he defined it as farming where annual precipitation is not considered sufficient for the production of profitable crops. Buffum (1909) further stated that "dry farming is usually carried on where the rainfall of one season is not sufficient and the moisture must be saved up for a longer period."

Even though Widtsoe (1920), Shaw (1909) and Buffum (1909) differed slightly in their preferred term for this new way of farming, they essentially used the same definition. More importantly, they all agreed that tillage was the key to success. Plowing in the fall as deep as possible was the general recommendation, usually 18–25 cm deep. This was to make a large enough reservoir to absorb and hold the moisture. Plowing was to be followed by disking in the fall or spring, followed by harrowing. Widtsoe (1920) stated "the all-important practice for the dry-farmer who is entering upon the growing season is cultivation. The soil must be covered continually with a deep layer of dry loose soil, which because of its looseness and dryness makes evaporation difficult." It is clear that they understood capillary water movement and that having loose soil on the surface with large pores would stop upward water movement. Widtsoe (1920) also understood the benefit of spreading straw or other litter over the soil. He reported the results of two studies showing reductions in evaporation of 22 and 38 percent with straw mulch on the surface. At the time, however, Widtsoe (1920) stated: "on the modern dry-farms, which are large in area, the artificial mulching of soils cannot become a very extensive practice, but it is well to bear the principle in mind."

The belief that deep plowing followed by shallow disking and harrowing to form a dust mulch on the soil surface was also strongly supported by H.W. Campbell who came from Vermont to South Dakota in 1879. Campbell had been inspired by the writings of Jethro Tull who had worked in England in the mid-1750s and was a strong advocate of intensive tillage. Tull concluded that thorough soil tillage produced crops that in some cases could not be produced by the addition of manure, and came to the erroneous conclusion that "tillage is manure" (Widtsoe 1920). While Tull's conclusion was incorrect, tillage does accelerate the decomposition of soil organic matter and increase soil fertility. This was certainly a benefit of tillage particularly before the widespread use of chemical fertilizer.

Campbell became a strong advocate of the dry-farm movement, particularly in the Great Plains that was previously called the Great American Desert and considered unsuitable for farming. Campbell grew wheat and other crops with considerable success in the late 1880s and in about 1895 began to publish Campbell's "Soil Culture and Farm Journal" (Widtsoe 1920). His writings were widely followed and led to the famous book "Soil Culture Manual" (Campbell 1907). Widtsoe (1920) summarized the Campbell system essential features as "the storage of water in the soil is imperative for the production of crops in dry years. This may be accomplished by proper tillage. Disk the land immediately after harvest; follow as soon as possible with the plow; follow the plow with the subsurface packer, and follow the packer with the smoothing harrow. Disk the land again as soon as possible in the spring and stir the soil deeply and carefully after every rain. Sow thinly in the fall with a drill. If the grain is too thick in the spring, harrow it out. To make sure of a crop, the land should be "summer tilled", which means that clean summer fallow should be practiced every other year, or as often as may be necessary."

With more and more successes of dryland farming, a wave of support developed. In 1907, the first Dry Farming Congress was held in Denver, Colorado. The USDA and state agricultural experiment stations also established dryland experiment stations throughout the Great Plains, some as early as 1903, that probably spurred dryland farming. In 1914, the USDA Division of Dryland Agriculture established field stations at 22 locations in the Great Plains (Fig. 1). World War I, coupled with high wheat prices and the development of power machinery, led to rapid expansion in cultivated land and large-scale production of wheat and other crops. Even marginal soils that should have been left in grass were plowed and seeded to wheat. This expansion in cultivated land took place primarily from 1915–1925 (Burnett et al. 1985). While various parts of the Great Plains experienced drought during the expansion of cultivated land, the Plains as a whole received average or better rainfall before 1930. The widespread drought of the 1930s, coupled with severe economic conditions and widespread wind erosion that was exacerbated by the dust-mulch

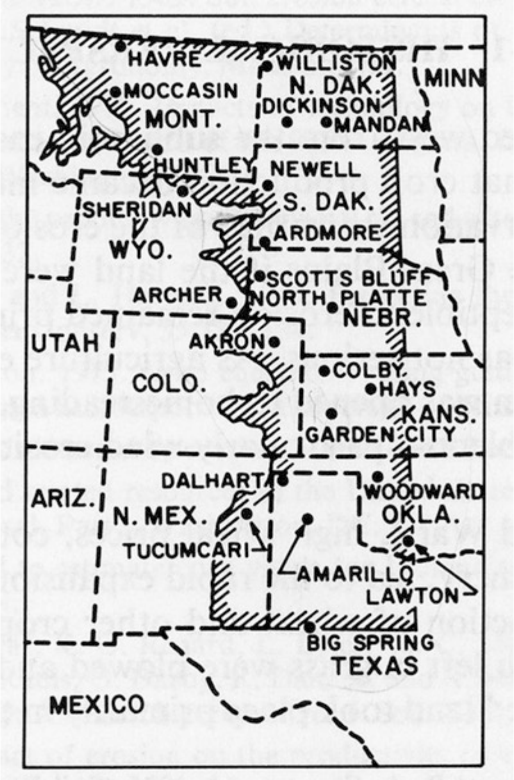

Fig. 1 Locations where dryland cropping experiments were conducted from 1903 to 1938 by USDA and State Agricultural Experiment Stations (Adapted from Cole and Mathews 1940)

tillage methods advocated by Campbell, resulted in the infamous Dust Bowl considered by many as the worst ecological manmade disaster in U.S. history. Surveys made during and shortly after the drought years of the 1930s in the southern Great Plains suggested that 43 percent of the area had serious wind-erosion damage. It was estimated that 2.6 million ha in the Southern Plains were removed from cultivation because of erosion but that about 10.3 million ha of less erodible soils made it through the drought cycle in sufficient condition to return to cultivation in the 1940s. With increased rainfall and higher crop prices in the early 1940s, the tendency to convert more grassland to cropland returned (Burnett et al. 1985).

3 The Dust Bowl Mandated a Change in Tillage

Extensive wind erosion during the Dust Bowl of the 1930s made it clear that changes had to be made. The intensive tillage that had worked so well in the beginning had greatly diminished the soil organic matter content leading to poor soil structure, lower infiltration, reduced water-holding capacity and uncontrollable wind erosion. Charles Noble of Alberta, Canada was one of the first to search for a cure. Noble concluded as early as 1916 that the once-favored “dust mulch” popularized by H.W. Campbell had to be abandoned (MacEwan 1983). This was not an easy decision for Noble to make because he had been a staunch disciple of the Campbell method embracing fine cultivation that inevitably pulverized the soil. However, Noble had observed neighbors that were using alternate strips of fallow and wheat as a means of controlling wind erosion. The standing stubble on the fallow prevented wind erosion on the fallowed land. Prairie farmers were challenged as never before to find some way of cultivating their fields without burying or sacrificing the ugly but precious stubble. Implements like the plow buried the stubble and all other vegetable residues completely, and the disc reduced the usefulness of the residue and buried much of it. Noble, working with agronomy teachers and others developed an important directive of southern Alberta, Canada; an important directive that was in stark contrast to the Campbell Soil Culture method. Their directives were (i) do not pulverize the soil with discs or harrows, (ii) use such implements as rod weeders, duck foot cultivators and spring tooth harrows that do not pulverize but leave a rough surface, (iii) if the shifting is small, a covering of manure or straw will sometimes save a whole field, (iv) reduce the extent of bare land by growing winter rye on part of the summer fallow, (v) consider working the farm in alternate strips of fallow and crop and (vi) co-operate with your neighbors–soil drifting can only be controlled by community action.

The strip cropping with fallow and wheat that started in 1918 was attracting attention and was sometimes considered plowless summer fallow or stubble mulching. Noble sensed the benefits from what was to become known as stubble mulch or trash cover and was searching for a way to cultivate for the destruction of weeds without destroying or burying the stubble and other vegetable residue from the previous crop. It would be unsightly but saving the soil was vastly more important than the house-cleaned appearance of a farm field (MacEwan 1983). This would be a vast departure from the plowing of the past. For generations, the plow was the symbol of farming. Good plowing was good farming; good farming was good plowing. Even the seal of the USDA has the moldboard plow as its centerpiece.

It was not until 1935 that the Noble Blade Cultivator was developed and played a crucial role in arresting soil erosion in the Canadian Plains and the western parts of the U.S. (MacEwan 1983). Noble was on a trip to California when he happened to see a California farmer using a straight blade tool to cut into the subsoil to loosen his sugar beets as an aid to lift them. The blade heaved the soil and disturbed weeds with little effect on the general appearance of the field. Noble immediately envisioned a machine that could cultivate the soil after harvesting a wheat crop to control weeds without depriving the land of its surface trash and standing stubble. He went directly to the home of a friend that had a shop attached and, with an old 3 m road grader, a borrowed forge and anvil, and being somewhat of a blacksmith, Noble constructed the first prototype. He tested it in a California orange grove and, while it did not work perfectly, Noble was pleased enough to take it to an advanced stage. He cut his planned stay in California short, loaded the crude cultivator onto a trailer, and headed home. Before it was time to start summer-fallowing, he had constructed four blade implements by pounding out new frames and blades making each one better than the last. Summer-fallowing that season was done with the four blades, and Noble was happy with the result. Neighbors and friends came to inspect the fields to satisfy themselves that the weeds had been controlled and that the stubble was still standing. Although Noble had not thought about manufacturing the plow, the plea from neighbors for one of his blades was so great that about 50 blade cultivators were constructed for local sale in 1937. The timing could not have been better because the worst dust storm in the history of the Plains area around Regina and Calgary, Canada hit on June 2, 1937 (MacEwan 1983). Nineteen of the 50 cultivators were purchased by the newly-formed USDA Soil Conservation Service and several others went to Canadian experiment stations for testing. In time, the straight bar was replaced by a V-shaped blade, but the effect was about the same, undercutting weeds and leaving stubble on the surface to blunt the force of wind and to catch and hold snow. Figure 2 shows a typical Noble Blade Cultivator. The V-shaped blades, often called sweeps, varied in size but the goal was always the same—to leave most of the crop residues on the surface. As a general guideline, about 75 % of surface residue cover remained on the surface following one operation. Unger et al. (2012) summarized the percentages of surface residue cover remaining after one pass with various implements.

Prior to the Noble Blade Cultivator, Fred Hoeme, a Hooker, Oklahoma farmer located in the center of the Dust Bowl area, developed a heavy-duty chisel plow in 1933 in an attempt to control wind erosion. He and his sons built and sold about 2000 of them from their homestead. In 1938, W.T. Graham purchased the manufacturing and distribution rights and established manufacturing in Amarillo, TX. The Graham-Hoeme plow was marketed as the “The Plow to Save the Plains” and was sold worldwide (Fig. 3). The chisel plow helped control wind erosion during the seven-year drought of the 1950s when precipitation was even lower than that during the Dust Bowl years of the 1930s. It was estimated that about half of the farmers in the Great Plains owned chisel plows. The chisels were often replaced with sweeps to achieve results similar to the Noble Blade Cultivator.

Fig. 2 Noble blade plow that ran about 10 cm below the soil surface to till the soil to cut roots of weeds without depriving the land of surface trash and standing stubble

Fig. 3 A Graham-Hoeme plow developed in 1933 and marketed as the "Plow to Save the Plains"

The Graham-Hoeme plow and the Noble Blade Cultivator brought an end to the emphasis on deep tillage and dust mulch that was earlier believed essential for dryland farming. These two implements were the forerunners of tillage implements used worldwide in dryland farming areas. In 2000, the Graham-Hoeme plow was dedicated as a National Historic Agricultural Engineering Landmark by the American Society of Agricultural and Biological Engineers and chisel plows and historic plaques are exhibited at Hooker, Oklahoma and at the USDA Conservation and Production Research Laboratory, Bushland, Texas.

4 Changing Tillage to Control Wind Erosion and Water Saving

Although Mr. Noble recognized that keeping residue on the surface would have a positive effect on soil water, particularly by trapping more snow, his primary focus was on controlling wind erosion. There is every indication that Mr. Hoeme focused entirely on controlling wind erosion. However, it became evident that the change from deep plowing and dust mulching to stubble mulching by using sweep and chisel plows resulted in more stored soil water in the soil profile during the fallow periods and increased yields of subsequent crops. Countless studies worldwide have shown that soil becomes air-dry to whatever depth the soil is plowed resulting in large losses of water. Therefore, farmers moved away from using dust mulch that had been widely promoted. Theoretically, dust mulch reduces water loss because plowing the soil to create the mulch forms large pores. Water cannot move from small pores into large pores by capillary action so the mulch prevents upward movement of water from the wetter soil below the mulch. However, by the time a soil can be tilled to create dust mulch, it has already dried to the point that capillary water movement has essentially stopped. Crop residues on the soil surface have other

Table 1 Progress in wheat–fallow cropping at the USDA Central Great Plains Research Station, Akron, Colorado

Years	Tillage	Number tillage operations	Fallow water storage[a]		Wheat yield (Mg ha^{-1})
			(mm)	(% precipitation)	
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)

[a] Fallow period of 14 months, mid-July to second mid-September

benefits such as preventing capillary action and keeping the soil cooler. Therefore, less intensive tillage and maintaining crop residues clearly increase water in the soil profile during fallow periods. Widtsoe (1920) recognized the benefit of having straw or manure on the soil surface but did not think it could be done in a practical way.

Peterson et al. (2012) summarized some studies that focused on increasing precipitation use efficiency in dryland agroecosystems. A long-term study that began in 1916 at the U.S. Central Great Plains Research Station, Akron, Colorado is a classic example of how a greater percentage of the precipitation occurring during a fallow period can be stored in the soil profile by decreasing tillage intensity and maintaining more crop residues on the soil surface. The results from 1916 to 1975 are presented in Table 1 along with projections for future years. Between 1916 and 1975, the number of tillage operations during the 14-month fallow period decreased dramatically resulting in more water storage in the soil profile for use by the subsequent wheat crop. Increasing soil water storage during the fallow period from 102 mm (19 % fallow efficiency) under maximum tillage to 157 mm (33 % fallow efficiency) using stubble mulch tillage more than doubled the yield of the following wheat crop (Table 1). Soil water storage increased because fewer tillage operations dried the soil less often and the newly-adopted tillage implements left more crop residue on the soil surface. Greb et al. (1979) predicted that adoption of no-till practices would increase fallow efficiency to 40 %. However, during the 1980s and 1990s, fallow efficiencies were generally less than 40 %, regardless of the climatic zone where the data were collected (Peterson et al. 2012). This is most likely due to insufficient crop residues being produced in dryland farming areas for the required surface mulch. Greb et al. (1967) and Unger (1978) showed that surface residue greatly increased fallow water storage, but residue amounts in excess of 6 Mg ha^{-1} were needed to achieve fallow efficiencies greater than 35–40 %. In the west-central Great Plains at wheat harvest, the maximum residue accumulation point in the system cycle, residue amounts commonly range from 2.2 to 5.6 Mg ha^{-1} (Peterson et al. 2012). The authors concluded that crop residues may not be feasible in dryland areas to increase fallow efficiency percentages above about 35 %. Nevertheless, the move away from intensive tillage in dryland areas to subsurface tillage and no-tillage systems has greatly reduced wind erosion and simultaneously increased precipitation use efficiency. This has significantly reduced wind erosion, slowed soil organic matter decline, increased crop yields and improved sustainability.

4.1 Conservation Agriculture

In recent years, there has been a worldwide focus on reducing tillage not only in dryland farming areas but in all climatic regions where crops are grown. The Food and Agriculture Organization (FAO) of the United Nations is the leading organization pushing this system, known as conservation agriculture (CA), but many other international, national and local entities are solidly behind the movement. While current crop production systems have often resulted in soil degradation and in extreme cases desertification, the adoption of CA technology has led to a reversion of these processes (Friedrich et al. 2012). CA is an approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (Friedrich et al. 2012). The authors characterized CA by three linked principles, namely:

1. Continuous no- or minimal mechanical soil disturbance (i.e., no-tillage and direct sowing or broadcasting of crop seeds, and direct placing of planting material in the soil; minimum soil disturbance from cultivation, harvest operation or farm traffic, in special cases limited strip tillage).
2. Permanent organic soil cover, especially by crop residues, crops and cover crops.
3. Diversification of crop species grown in sequence or associations through rotations or, in the case of perennial crops, associations of plants including a balanced mix of legume and non-legume crops.

CA principles are universally applicable to all agricultural landscapes and land uses with locally-adapted practices. However, the benefits and success of implementing CA successfully are perhaps the least in dryland farming areas because these areas are generally hotter and drier than more favored areas. Stewart et al. (1991) developed an index of temperature and precipitation that compares different climatic regions to the difficulty of developing sustainable agricultural systems, which are significantly more difficult in dryland farming regions (Fig. 4). However, CA grew out of dryland farming. Friedrich et al. (2012) stated that tillage, particularly in fragile ecosystems, was questioned for the first time in the 1930s when the Dust Bowl devastated wide areas of the mid-west United States. Concepts for reducing tillage

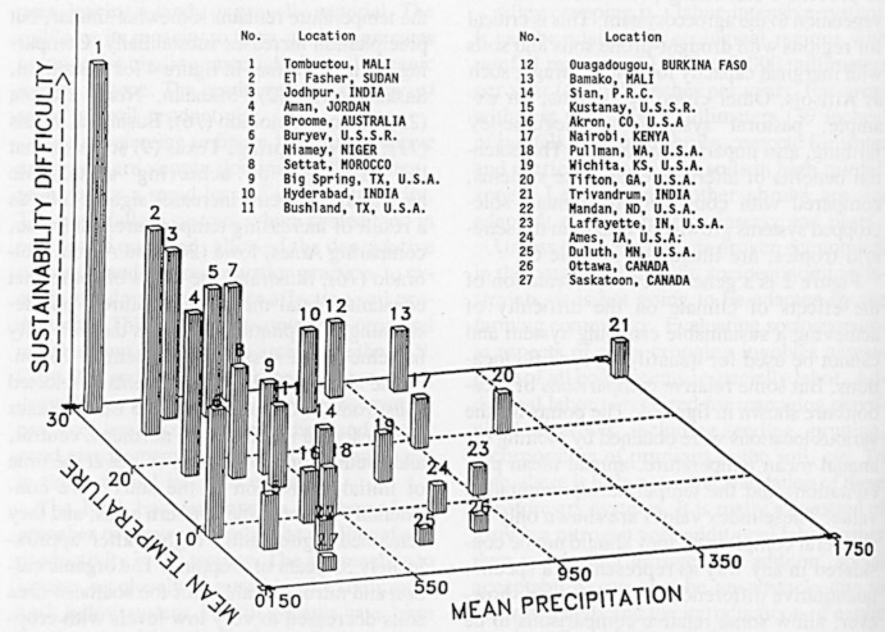

Fig. 4 Mean annual temperature and precipitation for various locations and temperature/precipitation as and “index” indicating the difficulty of developing a sustainable agriculture system (Stewart et al. 1991)

and keeping the soil covered with crop residues were developed and the term conservation tillage was introduced to reflect such practices aimed at soil protection. As discussed above, concepts for reducing tillage and keeping soil covered were developed and the term conservation tillage was introduced to reflect such practices aimed at soil protection. Unger (2006) stated that conservation tillage is any combination of tillage and planting practices that generally reduces the loss of soil and water relative to losses with conventional tillage. McCarthy et al. (1993) reported that conservation tillage is any tillage/planting system which leaves at least 30 percent of the field surface covered with crop residue after planting has been completed, and that this amount of cover will reduce erosion by at least 50 percent compared to bare, fallow soil.

In dryland farming areas, even when no-tillage is used between crops, there are often sufficient crop residues remaining after planting the next crop to cover 30 % of the soil surface. This is particularly true when only one crop is produced every two years, or two crops every three years, that result in long fallow periods between crops. As a result, current definitions of conservation tillage often do not include the 30 % minimum cover requirement. For example, CTIC (2015) states “conservation tillage is a system of crop production with little, if any, tillage. It increases the residue from the crop that remains in the field after harvest through planting. This results in increased natural recycling of crop residues.” The emphasis is on leaving last year's crop residue on the surface before and during planting operations to provide cover for the soil at a critical time of the year. The residue is left on the surface by reducing tillage operations and turning the soil less, even when the amount of residue is less than desired, particularly during drought years. Although this meets the first principle of CA in terms of minimal soil disturbance, it does not meet the second principle regarding soil cover based on the criteria that FAO uses to collect global data for adoption of CA. Global data of CA adoption are not officially reported, but collected from local farmer and interest groups. The data are assembled and published by FAO. For data collection, FAO has quantified the CA definition as follows (Friedrich et al. 2012):

1. Minimum Soil Disturbance: Minimum soil disturbance refers to low disturbance no-tillage and direct seeding. The disturbed area must be less than 15 cm wide or less than 25 % of the cropped area (whichever is lower). There should be no periodic tillage that disturbs a greater area than the aforementioned limits. Strip tillage is allowed if the disturbed area is less than the set limits.
2. Organic Soil Cover: Three categories are distinguished: 30–60 %, >60–90 % and >90 % ground cover, measured immediately after the direct seeding operation. Areas with less than 30 % cover are not considered CA.
3. Crop Rotations/Associations: Rotation/association should involve at least three different crops. However, repetitive wheat or maize cropping is not an exclusion factor for the purpose of this data collection, but rotation/association is recorded where practiced.

Therefore, even though CA largely stemmed from dryland farming, many dryland farming cropping systems do not qualify as CA systems due to the lack of sufficient crop residues. Limited precipitation and shorter growing periods allow only a small amount of crop residue to be returned to the soil. To make things worse, many dryland farming areas, especially in developing countries, have high rates of poverty and many crop residues are removed from the land for animal feed or for cooking and heating fuel. This can cause already low soil organic matter concentrations to become even lower resulting in lower soil quality. As already illustrated in Fig. 4, developing a sustainable cropping system becomes increasingly difficult in marginal climatic regions. However, adoption of reduced tillage and continuous cropping can increase dryland nitrogen (N) storage to a depth of 20 cm compared to a conventional farming practice, and hence, a no-till system provides better opportunities to sustain crop yields by growing more crops and to conserve soil carbon (C) and N more than the traditional tillage practice in the drylands of the U.S. Great Plains (Sainju et al., 2006). In the U.S. Northern Great Plains, continuous cropping with no-tillage improved soil and crop management practices and increased dryland soil C sequestration from 0 to 15 cm depth by 233 kg C ha^{-1} $year^{-1}$ compared to a loss of 141 kg C ha^{-1} $year^{-1}$ with conventional tillage (Halvorson et al. 2002). CA systems allow producers to increase cropping intensity because no-till conserves surface residues and retains water in the soil profile more than conventional tillage practices (Aase and Pikul 2000; Farhani et al. 1998). Similarly, data collected from Bushland, TX in the southern Great Plains showed that precipitation storage efficiency increased from 15 % with disk tillage to 35 % with no-till (Unger and Wiese 1979).

Table 2 Extent of adoption of conservation agriculture (CA) worldwide (countries with more than 100,000 ha in 2011)

Country	CA area (ha)	Country	CA area (ha)
United States	26,500,000	South Africa	368,000
Argentina	25,553,000	Venezuela	300,000
Brazil	25,502,000	France	200,000
Australia	17,000,000	Zambia	200,000
Canada	13,481,000	Chile	180,000
Russia	4,500,000	New Zealand	162,000
China	3,100,000	Finland	160,000
Paraguay	2,400,000	Mozambique	152,000
Kazakhstan	1,600,000	United Kingdom	150,000
Bolivia	706,000	Zimbabwe	139,300
Uruguay	655,000	Columbia	127,000
Spain	650,100	Others	409,400
Ukraine	600,000	Total	124,794,840

Adapted from Friedrich et al. (2012)

CA adoption worldwide has increased rapidly in recent years from 2.8 M ha worldwide in 1973/1974 to 6.2 M ha in 1983/1984, 38 M ha in 1996/1997, 45 M ha in 1999 and 72 M ha in 2003 (Friedrich et al. 2012). They stated that for the last 11 years reported, CA systems have expanded at an average rate of 7 M ha per year to increase from 45 M ha in 1999 to about 125 M ha in 2011 showing the increased interest of farmers in this production system. Countries with more than 100,000 ha of CA in 2011 are listed in Table 2.

The worldwide adoption of CA shows the dramatic shift away from tillage that was considered necessary and beneficial at the beginning of dryland farming in the mid-1800s. However, even with the increased adoption of CA, 125 M ha is less than 10 percent of the World's arable land (1396 M ha) (FAOSTAT 2015). Friedrich et al. (2012) consider that the main barriers to the adoption of CA practices continue to be: knowledge on how to do it (know how); mindset (tradition, prejudice); inadequate policies, for example, commodity-based subsidies (EU, US) and direct farm payments (EU); lack of availability of appropriate equipment and machines (many countries of the world); and lack of suitable herbicides to facilitate weed and vegetation management (especially for large-scale farms in developing countries). They also concluded that the roots of CA origins lie more in the farming communities than in the scientific community, and its spread has been largely farmer-driven. Experience and empirical evidence across many countries has shown that the rapid adoption and spread of CA requires a change in commitment and behavior of all concerned stakeholders. For the farmers, a mechanism to experiment, learn and adapt is a prerequisite. For policy makers and institutional leaders, the transformation of tillage systems to CA systems requires a thorough understanding of the large and longer-term economic, social and environmental benefits that the CA paradigm offers to producers and society at large.

4.2 Major Crops for Dryland Farming

Wheat (*Triticum aestivum* L.) was the leading crop in the beginning of dryland farming in the US (Widtsoe 1920) and remains so today in most regions. The crop is not highly drought-resistant and does not tolerate prolonged drought. Wheat is considered a drought avoidance crop which is well suited to dryland regions because it can take advantage of soil moisture that accumulates during fallow periods, winter and early spring, and matures before the hot and dry, late summer when planted at the appropriate time (Hansen et al. 2012). Similarly, under water-stressed growing conditions, wheat plants produce smaller cells reducing the height of the culm, the size of the leaves and the stomatal openings, and hence are less adversely affected by drought (Arnon 1972). Maize (*Zea mays* L.) was also a major crop in the beginning along with sorghum (*Sorghum bicolor* L.). Maize lost favor in semiarid regions because it was not considered as drought tolerant as wheat and sorghum. This is interesting because it was considered the most successful dryland crop in the early days of dryland farming (Buffum 1909; Shaw 1909; Widtsoe 1920). Widtsoe (1920) stated that of all the crops tried, maize was the most uniformly successful under extremely dry conditions and he felt that the dryland community had yet to realize the value of maize as a dryland crop. He stressed, however, that the value in dry years was as a fodder crop because grain may not be produced. These early writers stated that maize grown in dry areas should be planted in hills of multiple plants per hill. Sorghum is grown largely in regions of Africa, Asia, North America and Australia that are too dry for successful maize production. Sorghum produces higher grain yield than maize under dry and hot climatic conditions because it remains dormant during the period of severe water stress and resumes growth when favorable conditions reappear (Leonard and Martin 1963).

Cotton (*Gossypium hirsutum* L.) is also a major crop in dryland areas where there is a sufficient frost-free growing season of at least 180 to 200 days, ample sunlight and enough growing heat units accumulated during the growing season. Sunflower (*Helianthus annuus* L.) is cultivated in some dryland areas; it has a deep rooting system capable of extracting water and nutrients to a depth of 3 m, which contributes to its adaptation to dryland environments (Jones and Johnson 1983). Since there is a close relationship between plant available water in the soil profile during the reproductive period and total biomass production, plants with high water use efficiency (WUE) are important for determining crop yield under dryland environments (Blum 2009). Crop yields have increased significantly in most dryland farming regions over the years. For example, in Whitman County, Washington winter and spring wheat yields have increased from less than 2000 kg ha^{-1} to about 5000 kg ha^{-1} over 73 years (Fig. 5), an average of 48 kg ha^{-1} $year^{-1}$. However, the data points indicate that yields may have plateaued during the 1980s. There are many reasons for the increased yields, but there is little doubt that the main driver has been reducing water loss by evaporation and runoff so more water is available for the plants. This is because the units of water to produce a unit of biomass for crops have changed little, if any. Widtsoe (1920) reported that German scientists, in

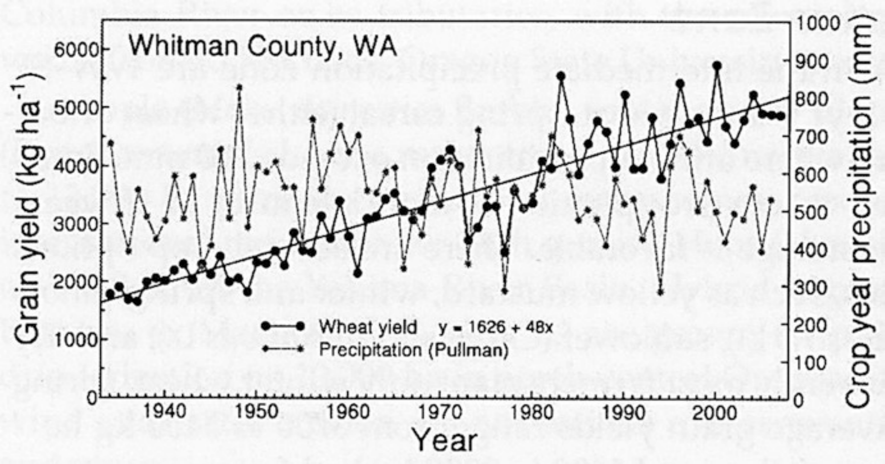

Fig. 5 Long-term county-wide dryland wheat grain yield in Whitman County, Washington, superimposed with crop-year precipitation from Pullman, WA (Source: Schillinger et al. 2010)

the late 1800s, reported that 233 units of water were required for one unit of corn dry matter and 338 units for a unit of wheat dry matter. The studies were done in a humid environment so it can be assumed that most of the water use was for transpiration. Sinclair and Weiss (2010) reported that a C_4 grass growing in a somewhat average transpiration environment (examples include maize and sorghum) have a transpiration rate of approximately 220 units water for each unit of plant growth. A C_4 species (includes wheat) growing in the same environment will transpire about 330 units of water for each unit of dry matter produced. Stewart and Peterson (2015), based on field data, recently estimated that the transpiration rates of maize and grain sorghum are generally between 225 and 275 g of water per g of biomass production in the U.S. Great Plains region. Therefore, increased yields over time like those shown in Fig. 5 cannot be attributed to more water efficient crop cultivars since no significant change in the units of transpiration required to produce a unit of biomass for a given species appears to have occurred. Accumulation of plant biomass is directly related to water availability (Sinclair 2009). Sinclair states that the difference in vapor pressure inside and outside the leaf (VPD) controls water loss through the stomata. VPD in arid regions is large because the vapor pressure of the atmosphere is very low relative to humid areas. For a given environment, VPD cannot be controlled—it is what it is. Sinclair further stated “despite claims that crop yields will be substantially increased by the application of biotechnology, the physical linkage between growth and transpiration imposes a barrier that is not amenable to genetic alteration.” While many plant scientists disagree, there is little evidence to repute it (Gurian-Sherman 2012). Therefore, the increased yields shown in Fig. 5 are most likely due to improved water management that increased ET and to improved cultivars with higher harvest index (HI) values. HI is the weight of grain divided by the weight of aboveground biomass which increased significantly in wheat with the development of short-straw cultivars. Fischer et al. (2014) also concluded that there is little hard evidence that plant breeding has increased transpiration efficiencies and that higher HI values account for much of the increased yield in recent years. However, Berry et al. (2007) concluded that there appears to be little scope for further increases in HI beyond 0.55 to 0.60 in crops that bear aboveground grain because such crops depend on a stable structure to distribute leaf area, support grain and prevent lodging.

4.3 Potential to Enhance Water Productivity in Dryland Farming

Wani et al. (2012) stated that there is vast untapped potential to increase yields in rainfed areas with appropriate soil and water interventions. They indicated that a linear relationship is generally assumed between biomass growth and ET, which describes water productivity between 1000 and 3000 m^3 t^{-1} (1000 to 3000 kg water per 1 kg grain) for grain production (Fig. 6). Below yield levels of 3 t ha^{-1}, however, they state that this relationship does not hold true and this coincides with the yield levels of small and marginal farmers in dryland areas. Water productivities range from 5000 to 8000 m^3 t^{-1} when grain yields are as low as 1 t ha^{-1}. Wani et al. (2012) state that evidence from water balance analyses in farmers' fields around the world shows that only a small fraction, less than 30 % of precipitation, is used as plant transpiration to support plant growth.

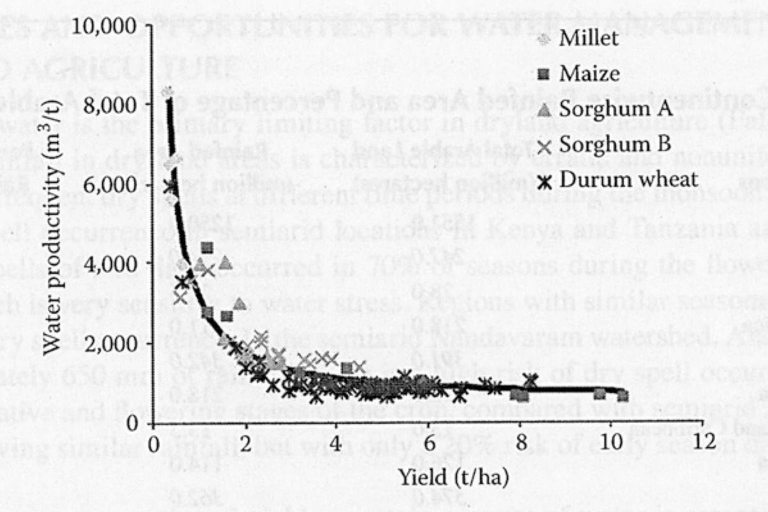

Fig. 6 Yield relationship between water productivity and yield of cereal crops in different climatic conditions and management (Source: Wani et al. 2012)

A graphical model of the water balance for a wide range of climatic conditions (Ponce 1995) is presented in Fig. 7. This model was based on the range of climates in the Sertao region of Brazil, but it exemplifies important differences in how water is used over a range of climatic zones. Although Fig. 7 is only conceptual, and ignores drainage regardless of the amount of precipitation, it does illustrate important points. Most importantly, it shows that only a small proportion of annual precipitation in arid regions is used for ET and that a large proportion is lost as evaporation during the time that crops are not being produced. Furthermore, a large part of ET is lost as evaporation from the soil surface during the growing season such that the amount of water used in arid areas for transpiration is small, and it is this water that increases biomass. Studies have shown that for the semiarid southern U.S. Great Plains, about 50 % of annual precipitation is used for ET and about 50 % for transpiration, so 25 % or even less is transpired. Wani et al. (2012) stated that in arid areas as much as 90 % of precipitation can be lost as evaporation and 10 % for transpiration. These estimates support the concept illustrated in Fig. 7. While these low percentages of precipitation used for transpiration support the view of Wani et al. (2012), that there is untapped potential for using water more efficiently, they also point out the challenges of successfully tapping into this potential. There are three basic strategies for increasing crop yields in dryland cropping systems: (1) increase the capture of precipitation by reducing runoff and storing it in the soil profile for later use by the crop for ET, (2) increase to the fullest extent feasible the portion of ET that is used for transpiration relative to that lost by evaporation from the soil surface and (3) ration water use so that early vegetative growth does not use all of the plant available water in the soil profile so that some is available during reproductive and grain-filling periods, particularly for grain crops. These strategies led to the more than doubling of wheat yields in Whitman County, Washington discussed earlier with Fig. 5. Although the average annual precipitation has remained fairly constant, a greater percentage is likely to have been stored in the soil profile for use by subsequent crops, and the mulch left on the soil surface reduced evaporation during the growing season, so that a higher percentage of annual precipitation was used for transpiration. As illustrated in Fig. 7, increasing yields in semiarid regions depends on increasing the portion of precipitation that is used for ET, and increasing the portion of ET that is used for transpiration.

Stewart and Peterson (2015) stated that the grain yield (GY) of a crop can be expressed by:

$$\mathrm{GY} = \mathrm{ET} \times \mathrm{T} / \mathrm{ET} \times 1 / \mathrm{TR} \times \mathrm{HI} \tag{1}$$

where GY is kg ha^{-1} of dry grain yield, ET is kg ha^{-1} of ET (water use by evaporation from the soil surface and transpiration by the crop between seeding and harvest), T/ET is the fraction of ET transpired by the crop, TR is the transpiration ratio (kg water transpired per kg of aboveground biomass) and HI is harvest index (kg dry grain/kg aboveground biomass). All weights are dry weights, so GY values should be adjusted before comparing with field grain weights that usually have 12–15 % water content. While this equation applies to all situations where grain

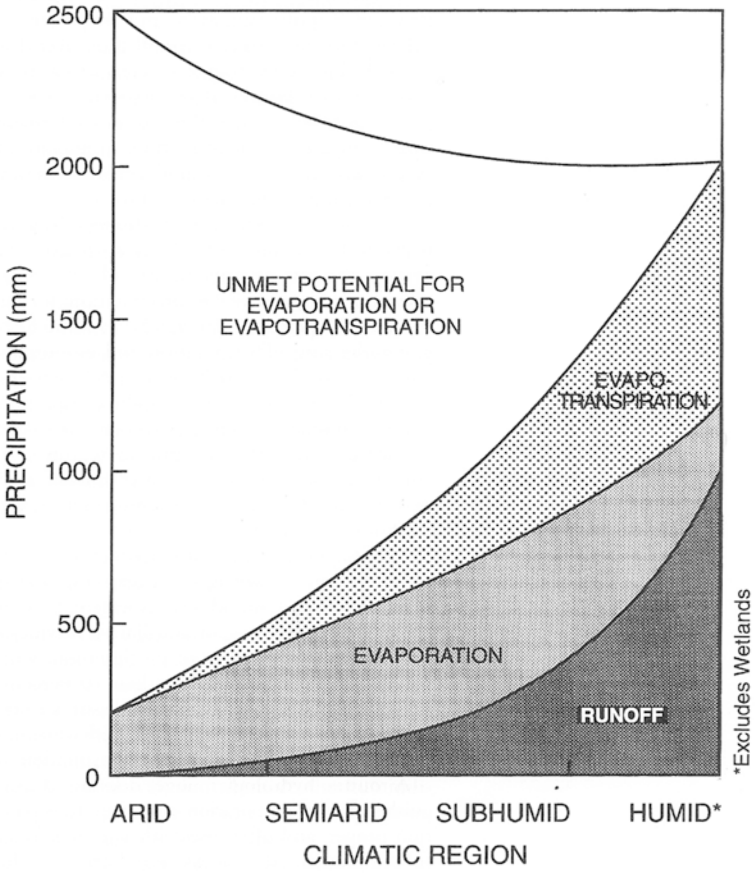

Fig. 7 A graphical model of the water balance for a wide range of climatic conditions (Source: Ponce 1995)

crops are produced, the range of values for each of the components becomes considerably greater and more variable in dryland farming regions. Average annual precipitation in dryland farming regions is generally less than 500 mm, so ET amounts are commonly below 250 mm even when annual cropping is practiced, and perhaps about 350 mm when a fallow period is used prior to seeding a crop. The T/ET values usually range between 0.50 and 0.75 with the lower values associated with limited water. Sinclair and Weiss (2010) stated that the TR for crops like maize and sorghum is about 220 when grown in a somewhat average transpiration environment, but could be about 280 for an arid environment and as low as 160 for a humid transpiration environment. HI values can also vary considerably. Prihar and Stewart (1990) reported upper values of HI for maize, grain sorghum, and wheat of about 0.60, 0.56, and 0.47, respectively. However, the lower values depended mainly on the amount of stress. Under dryland farming conditions, HI values are often below 0.30 and under extreme water stress, values can equal or approach zero.

Others, including Passioura (1977), French and Schultz (1984), and Connor et al. (2011), have developed equations that link grain yield with T, ET and HI. Eq. (1), however, includes all four factors that affect grain yield; since changing any one factor almost always changes the other factors, it can be easily used to evaluate how changing management practices will likely affect grain yields. Stewart and Peterson (2015) discussed each of the components for dryland regions and strategies for their improvement. Since Eq. (1) is linear, increasing any one component by 5 % will increase grain yield by 5 %. Therefore, large increases in yield only occur when all of the components increase and this generally happens when ET increases. Stewart and Peterson (2015) presented hypothetical component values for maize growing in areas of annual precipitation ranging from 500 to 1000 mm that showed doubling ET increased grain yield 4-fold. Increasing ET usually favors the other components. However, some common strategies used for growing grain crops in dryland farming areas where ET amounts are low often result in some components becoming less favorable. For example, when growing season ET is expected to be low, producers commonly reduce plant populations significantly. If this is not done, plant available water in the soil profile is used early for vegetative growth leaving little or no water for the reproductive and grain-filling stages. Looking at Eq. (1), however, reducing plant populations sometimes results in failure to exploit all of the plant available water in the soil profile. Lower plant populations also reduce canopy cover such that the increased bare ground increases evaporation from the soil surface resulting in a lower T/ET component. In addition, with the plants further apart, the microclimate is less favorable so TR increases because more units of water must be transpired to produce a unit of biomass. Thus, reducing plant populations in dryland farming areas is considered an essential practice, but it tends to make every component in Eq. (1) less favorable apart from HI which in reality means reducing the plant population is to avert risk of failure rather than to increase yield. Another common strategy in dryland farming is to use skip rows or leave wider spaces between rows. Again, this practice makes all of the components in Eq. (1) less favorable apart from HI. As a result, it is exceedingly difficult to increase yields in dryland farming regions where ET amounts are low. Eq. (1) also illustrates why mulch is important for dryland farming because it increases soil water storage during a fallow period thereby increasing ET, and it significantly increases the T/ET component leading to a better canopy that improves the microclimate that tends to reduce TR. Without question, reducing tillage and leaving more crop residues on the soil surface has been the main reason for increased yields in dryland farming regions like those shown in Fig. 5 for Whitman County, Washington. In many dryland farming regions, however, there are not sufficient crop residues produced for adequate mulch, or the residues are used for animal feed or fuel.

A relatively new strategy for dryland farming is growing grain sorghum or maize plants in clumps rather than equally spaced in rows (Bandaru et al. 2006; Kapanigowda et al. 2010; Krishnareddy et al. 2010). The hypothesis is that clumped plants, particularly grain sorghum, will produce fewer tillers that use water and nutrients, produce little or no grain when water is limited, improve the microclimate to lower vapor pressure deficit, and fully use plant available soil water during the growing season. A possible disadvantage is that less shading of the soil surface might lower the T/ET component so it is recommended that clump planting is combined with mulching. Although growing maize or grain sorghum in clumps is not expected to increase yield substantially, the practice has potential because it is easily done with existing equipment with no additional input cost. The use of clumps as well as skip rows is based on the principle of non-uniformity (Loomis 1983; Connor et al. 2011). These authors stated that when a soil resource such as water is limiting, non-uniform treatment of the land or crop can be an advantage. Where soil resources are non-limiting, however, they stated that uniform cropping will provide the greatest efficiency in light interception and photosynthesis. It is of interest that both Shaw (1909) and Buffum (1909) emphasized in their early writings that maize grown for grain in dryland areas with less than about 400 mm average annual precipitation should be planted in hills with at least four stalks. They stressed that pollination significantly improved in maize plants growing in hills.

Stewart and Peterson (2015) suggested that the best strategy for crop production in dryland farming areas may be to grow forage rather than grain crops. A careful analysis of Eq. (1) supports this suggestion because the HI component is eliminated and concern about crop failure is diminished. Therefore, a larger plant population can be used that will more fully utilize growing season precipitation and stored soil water, shade more of the soil surface to improve the T/ET component, and improve the microclimate that tends to decrease the TR value. The forage can be removed as hay or silage, or grazed by animals which is perhaps the best strategy because most of the nutrients are recycled to the soil with the manure. Therefore, in cases where it is feasible, the best way to capture the potential of dryland farming areas is to develop crop–livestock systems.

4.4 Conservation Bench Terraces

The primary goal in dryland farming regions is to capture precipitation where it falls, use it immediately for a growing crop or store it in the soil profile for later use by plants. There are situations, however, where it can be advantageous to harvest water from a larger area and concentrate it on a smaller area. Oweis et al. (2012) and Koohafkan and Stewart (2008) summarized some of the benefits and constraints of water harvesting. Water harvesting is perhaps best used in areas where average annual precipitation is too low for commonly-accepted dryland farming practices and where crops can only be grown after concentrating runoff water. Therefore, water harvesting is generally not considered a common dryland farming practice. An exception is the conservation bench terraces or Zingg terraces developed in the U.S. as a type of rainfall multiplier for use on large-scale mechanized farms (Zingg and Hauser 1959). As depicted in Fig. 8, bench terraces use part of the land surface as a catchment to provide additional runoff onto level terraces where crops are grown. However, the catchment areas can also be used for cropping but generally

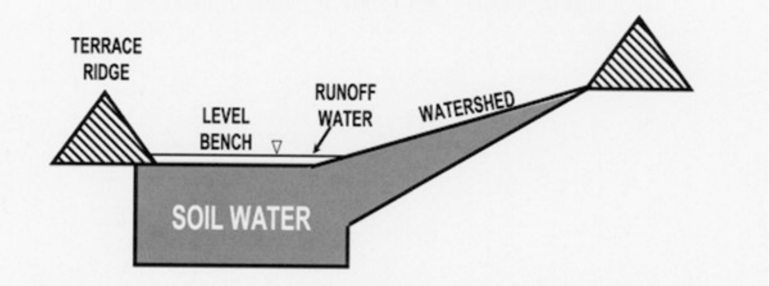

Fig. 8 Cross-sectional diagram of a conservation bench terrace that concentrates runoff water from an adjacent catchment area to a level bench (Modified from Baumhardt et al. 2008)

only one crop every two years or two crops in three years to allow for long fallow periods between crops. Conservation bench terraces have also been successfully developed in semiarid and subhumid regions of India. Sharda et al. (2002) conducted a study in India and, compared to the conventional system of sloping borders, the conservation bench terrace reduced surface runoff from 36.3 to 7.4 % of rainfall and soil erosion from 10.1 to 1.19 t ha^{-1} $year^{-1}$.

Water running off the catchment area is retained on a level bench for annual cropping. The terraces are designed for use on sloping lands of about 1–2 % with the catchment areas about twice as wide as the level terrace. The width of the terraces is usually at least 25 m to be compatible with tillage and harvesting equipment. However, the width can be constrained by the slope because wide level terraces require large amounts of soil movement to make the level terrace which make it cost prohibitive and create fertility problems on some soils because soil has to be removed from one side of the level terrace and to the other. The hypothesis is that the catchment area can still be farmed without serious yield reductions and the runoff water can be captured on the level terrace to make it more productive. For example, assuming average annual runoff from a field is 50 mm and the catchment area is twice as wide as the level terrace, the level terrace would not lose any water from runoff and would receive 100 mm from the catchment area so the level terrace would have 150 mm more water for crop production than the catchment area. Although the concept has worked well in some areas, the practice has not been widely accepted because of the constraints already listed. Unger and Stewart (1983) briefly reviewed the design of experimental conservation bench terraces at several locations in the U.S. Great Plains. The constraints are greater for large-scale producers as the equipment is on a larger scale and the construction of terraces and land leveling has become more costly. In recent years, controlling water erosion has shifted away from using terraces to some form of conservation tillage that leaves sufficient mulch on the surface to increase infiltration and reduce runoff. Conservation bench terraces, however, are effective and should be considered when feasible, particularly for small holder farmers.

5 Gravel and Plastic Mulches

Although the use of crop residues for mulch is the focus of dryland farming, particularly on large-scale operations, other forms of mulch play an important role in producing crops in low precipitation areas in some countries such as China. In some marginal areas of China, where annual precipitation is 200 to 300 mm, farmers have survived for many generations (Liang et al., 2012) by applying a 10 cm thick layer of porous gravel on the soil surface. This lessens the risk of crop failure, which commonly occurs as a result of low precipitation and high evaporation. Such gravel-based systems have existed for at least 200 to 300 years with some evidence that they date back 400 to 500 years. Even today, new areas are being developed in several counties of Gansu Province and other areas of northwest China. Liang et al. (2012) estimated that 170,000 ha of cropland in these areas are being farmed using gravel mulches. Although such methods have severe labor constraints, they clearly illustrate the effectiveness of mulch for conserving water in dryland areas. The gravel mulch is effective in reducing soil surface evaporation and runoff, improving water infiltration and increasing soil temperature (Xie et al. 2010).

In contrast to the historical use of gravel for mulch, plastic film is increasingly being used in crop production systems. Although frequently used in developed countries with high-income crops, it has been widely used in China in dryland farming areas. With limited available land for agricultural expansion, China has used plastic film mulch extensively to reduce soil evaporation and weed populations, increase soil temperature and enhance crop transpiration. It has been widely used for the production of cereals, vegetables, oilseeds, fruits and other crops. China uses 40 % of the world's plastic mulch (Ingman et al. 2015). In 2011, 1.2 M t of plastic film was applied to 19.8 M ha of cropland in China, equivalent to 12.2 % of the arable land (Ma 2013; Zhang 2013). While it is unlikely that plastic film will be used on large-scale commercial farms due to water runoff problems and other constraints, its use has greatly increased crop production on smallholder farms in China. This practice can capture the potential of low rainfall regions because it drastically reduces the evaporation of water from the soil surface during the growing season so that a high percentage of ET is used by plants as transpiration that is directly related to biomass production. In 2012 in Gansu Province, 92 % of the 896,000 ha of maize was produced using plastic mulch (personal communication, Dr. Fan Tinglu, Gansu Academy Agricultural Science, Langzhou). Several field experiments have shown that plastic mulch can modify soil moisture and temperature, both of which control near-surface biological processes including seed germination, plant growth and insect population dynamics (Anikwe et al. 2007; Wang et al. 2011). Plastic film usage does present some environmental problems as it is difficult to dispose of after it is no longer usable. This is commonly called baise wuran, the 'white pollution' in China. Biodegradable films are being developed that may alleviate this problem in the future. This practice has not been widely used for dryland farming outside of China and is generally not considered feasible for large commercial farms. However, it demonstrates the effectiveness of mulch for capturing potential for increasing crop production in dryland farming regions.

5.1 Future and Challenges of Dryland Farming

The challenge for global agriculture in the twenty-first century is to produce 70 % more food and fiber by 2050 for a growing and more prosperous population while implementing more sustainable methods of farming and responding to climate change (FAO 2009). As incomes rise, people tend to eat fewer grains and increase their consumption of meat and other animal-based products. Dryland farming areas must play an important role in meeting this challenge.

Dryland farming areas are largely semiarid and have unique characteristics. Bowden (1979) lists four management keys that must be understood and applied as new strategies and practices are developed:

1. No growing season is or will be nearly the same in precipitation amount, kind, or range, or in temperature average, range, or extremes, as the previous growing season. Although this is true for all rainfed cropping systems, it requires absolute attention in dryland farming. Crop cultivation requires adjustment every year, which leads to the second key.
2. Crops cannot be planned or managed in the same manner from season to season. Most of the practices in either humid or arid areas have some predictability on an annual basis. In semiarid climates, however, even highly mechanized, technically advanced, commercial farms such as those in the High Plains of North America or the outback of Western Australia do not have sufficiently stable production for the individual or government to count on for a given production figure for the following season.
3. Soil and water resources do not remain the same for any extensive period of time once agriculture is introduced. Most semiarid cropland suitable for cultivation is developed under grass or scattered shrubs on relatively flat topography. The competition for water and nutrients to produce crops requires removal of the protective cover. Because appropriate crops are annual and dependent on precipitation, severe drought often leaves the soil highly vulnerable to wind erosion.
4. There is abundant sunshine due to many cloud-free days. Abundant sunshine means higher temperatures that induce rapid growth, but it also demands careful management of soil water. It is possible for a grain crop to mature rapidly due to several weeks of sun-drenched, rainless conditions and desiccate just days before ripening. It is also possible for a few millimeters of precipitation to occur at almost the last moment to produce a good grain crop.

The four key points outlined above have always been challenging, but they are even more so today in view of the increased environmental concerns and the threat of climate change. The challenges are to increase resilience and to achieve and maintain the sustainability of dryland agriculture. The public at large is increasingly demanding sustainable systems, although their demands are not always clear. There are many definitions of sustainable systems, sustainable agriculture, sustainability and other terms that are difficult to interpret and often not feasible to implement.

The American Society of Agronomy (1989) stated “A sustainable agriculture is one that, over the long term, enhances environmental quality and the resource base on which agriculture depends; provides for basic human food and fiber needs; is economically viable; and enhances the quality of life for farmers and society as a whole.”

There are clearly times that dryland farming regions fall short of meeting all the requirements for a sustainable system. The infamous Dust Bowl that occurred in the U.S. and Canada during the 1930s is considered by many as the worst ecological disaster in North America and it was directly associated with dryland farming. Some of the removed cropland was returned to grassland, and drastic changes were made in tillage and other management practices to improve sustainability. There is little doubt that considerable areas of dryland farming are economically viable only because of government policies that provide subsidies or insurance programs to provide some income during drought years. There are no standard guidelines that can be applied to determine the sustainability of dryland farming regions because it will depend on local, regional and country conditions. However, the adoption of conservation agriculture that is based on continuous minimum mechanical soil disturbance, permanent organic soil cover and diversification of crop species grown in sequences and/or associations should be applied to the fullest extent feasible in all dryland farming systems. These principles will enhance or maintain soil physical, chemical and biological properties to assure continued crop production and to prevent wind and water erosion from degradation of the environment. Therefore, successful dryland farming requires favorable soils that can hold moisture and supply nutrients to growing plants, crop cultivars that can withstand climatic abnormalities, and growers who can tailor crop management practices according to the local climatic conditions.

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