REDUCING DROUGHT EFFECTS ON CROPLANDS IN THE WEST-CENTRAL GREAT PLAINS

UNITED STATES
DEPARTMENT OF
AGRICULTURE

AGRICULTURE
INFORMATION
BULLETIN
NUMBER 420

PREPARED BY
SCIENCE AND
EDUCATION
ADMINISTRATION

ABSTRACT

Greb, B. W. 1979. Reducing drought effects on croplands in the west-central Great Plains. U.S. Department of Agriculture Information Bulletin No. 420, 31 pp., illus.

The drought of 1977 in much of the Midwest and Western United States again called attention to the need for improved management of our limited water resources in all segments of society. Water conservation concepts and practices for use on dry cropland with some interpretation on irrigated cropland are given for the west-central Great Plains. Strategies are discussed for improved water intake efficiency, including systems to upgrade the quality of summer fallow, snow control, reducing runoff water, irrigation, and deep plowing. Additional strategies are presented for improving water use by crops through soil fertility, better plant stock, matching plant populations with water supply, various cultural manipulations, and improved timing of irrigation. Wind and water erosion—brought about by prolonged drought—and their control are briefly outlined. Results show significant progress of many facets of water management at the research level, some of which have been transferred into commercial farming channels. The transfer of established and new water conservation concepts and practices for cropland will likely be faster and with greater diversity than in the past because of energy and economic pressures.

Keywords: central Great Plains, drought, dryland, erosion, evaporation, herbicide, irrigated, runoff, snow barriers, stubble mulch, summer fallow, terraces, tillage, water use, weeds, winter wheat.

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Stock Number 001-000-03978-4

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Issued June 1979

REDUCING DROUGHT EFFECTS ON CROPLANDS IN THE WEST-CENTRAL GREAT PLAINS

By B. W. Greb[1]

I. INTRODUCTION

Problem Review

Despite vast new technology, the severe drought of 1977 in the Western United States was a rude reminder that people do not yet control the whims of nature. Record low snowfall in the winter of 1976-77 was received in all major western mountain watersheds, including the Cascades of the Pacific Northwest, the High Sierras in California, the Basin Ranges, and the entire Rocky Mountain system from northern Montana to New Mexico. Spring and summer rainfall shortages continued in the mountains and intermountain rangelands and encroached onto the Great Plains. The major drought area extended from International Falls, Minn., diagonally southwest to El Paso, Tex. Smaller pockets of drought prevailed east of this line. This area was delineated and some of the causes and effects of the drought were theorized by Canby (*5*).[2]

As our culture becomes more sophisticated, the impact of drought becomes potentially more devastating. In 1977, greatly reduced streamflow affected power generation for a high energy consuming public, reduced irrigation allocations on millions of acres of high-production western land, threatened long-established fisheries and wildlife, and suppressed the market of small industries dependent upon recreational income. In the uplands, the forest fire hazard rose quickly, and the lack of range grass production for livestock became critical. On the Great Plains, two of the larger duststorms in recent times were triggered February 23 and March 10.

Drought is not new. It is a natural happenstance of all lands except tropical rain forests, and even rain forests have fluctuations of precipitation well below the norm. Biblical history cites numerous examples of drought back to Joseph's time in Egypt. More than one ancient civilization was destroyed by prolonged drought. Our own Southwest Indian cultures abandoned pueblo villages and cliff dwellings because of protracted dry cycles. The "dirty 30's and 50's" on the Great Plains are still fresh in our memory.

What is drought? A good definition is elusive. Some people say it means too little rainfall (or snowfall) that comes too late for our immediate needs. But what are the demands for water? In our haste to settle the West, we sometimes created needs that could only be fulfilled by above-normal rainfall and made little allowance for below normal rainfall. Over estimation of streamflow expectancy is a good example. Dryland farming to the edge of the desert is another.

On the Great Plains, drought is sometimes defined as an arbitrary percentage of precipita-

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[2]Italic numbers in parentheses refer to Literature Cited, p. 29.

tion in a given time period that is below the long-term average. Precipitation that is less than 75 to 80 percent of the norm for a year usually spells trouble in the Great Plains, especially if precipitation in previous or succeeding years was less than normal. These rainfall deficits may soon become soil water deficits that result in curtailment of plant growth and crop failure.

The entire scope of drought is much too broad to be covered here. The purpose of this report is to outline a summary of strategies for drought as pertaining to domestic agricultural crops within the west-central Great Plains with occasional reference to the northern and southern Great Plains. By no means have all drought strategies been discovered, but those presented here are believed to have wide application outside the Great Plains.

Reducing the impact of drought involves a two-pronged approach—(1) using systems that do a better job of storing the rainfall and snowfall that reaches the earth and (2) using systems that convert this water into more usable plant material per unit of water. These systems, or strategies, are then applied within the realistic resource limits of land and climate.

Land and Climate

The U.S. Central Great Plains Research Station, Akron, Colo., serves approximately 55 million acres of this region. The area includes cropland, rangeland, and irrigated land in eastern Colorado, western Nebraska, western Kansas, and southeastern Wyoming. The present general land use in the west-central Great Plains is given below:

Land use	*Million acres*
Winter wheat	9.0
Summer fallow	8.7
Other dryland crops	5.3
Irrigation	7.0
Rangeland	25.0
Total	55.0

The land resource areas falling within the Station's area of research responsibility include the central high plains, the upper Arkansas Valley rolling plains, and the central tableland. These areas have varying climatic conditions and types of farming operations. The soils are principally derived from wind deposits and outwashes from Rocky Mountain sources. Topography ranges from nearly level to gently rolling at elevations ranging from 2,200 to 6,100 feet above sea level. The soils are typically calcareous, but vary widely in depth, texture, fertility, water-holding capacity, and erodibility.

The boundaries of the semiarid west-central Great Plains (fig. 1) extend from roughly the 100° meridian in Kansas and Nebraska to the base of the Rocky Mountains. The climate is classified as cool-semiarid. As such, water is the most limiting resource for optimum crop and rangeland production. In general, the climate becomes warmer and drier north to south and warmer and wetter west to east. Annual precipitation varies from 12 to 22 inches with a 17-inch average. Annual snowfall ranges from 15 to 40 inches and contributes 8 to 30 percent of the total precipitation. Mean annual temperature is 50°F and varies from 46° near the north-northwest edge to 56° near the south-southeast edge of the area.

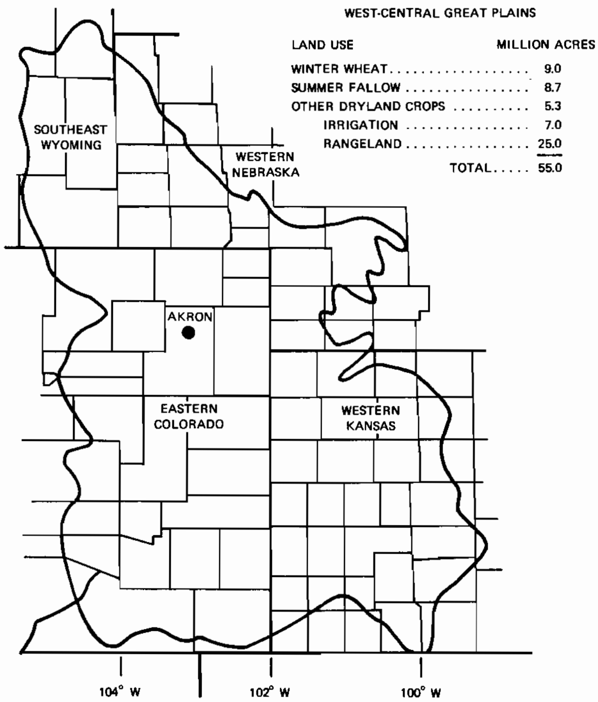

FIGURE 1.—Area of research responsibility of the U.S. Central Great Plains Research Station.

Predominant cash crops are winter wheat, sorghum, and millets on the dryland, and sugar-beets, corn, alfalfa, beans, and barley on the irrigated land. Approximately 55 percent of the area is cultivated and 45 percent is rangeland. Consequently, livestock production on rangeland accounts for a significant proportion of the agricultural income.

Drought Probability

The annual precipitation data at Akron for 1908-76 are shown in figure 2 and are typical of the highs and lows at Great Plains locations. With the exception of the wet 1940's, the trend of the amount of precipitation since early in the century is downward, especially since 1950 as shown by the drought danger line in figure 2. Data from

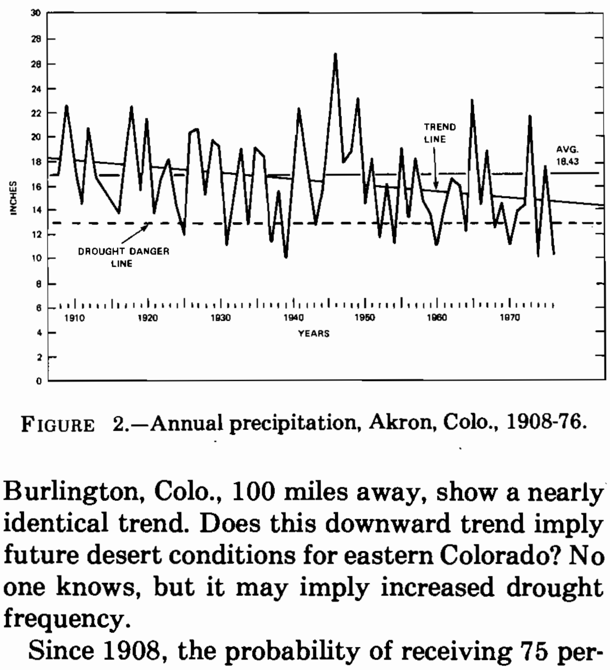

FIGURE 2.—Annual precipitation, Akron, Colo., 1908-76.

Burlington, Colo., 100 miles away, show a nearly identical trend. Does this downward trend imply future desert conditions for eastern Colorado? No one knows, but it may imply increased drought frequency.

Since 1908, the probability of receiving 75 percent or less of annual precipitation at Akron and Burlington occurred 20 and 28 percent of the time, respectively. Agriculturally, 75 to 80 percent of normal precipitation is a danger signal for potential stress to dryland crops and winter wheat in particular. In some years, favorable snowfall, which is more efficiently stored as soil water reserves needed for crops than hot summer showers, will offset reduced total precipitation, and little drought stress occurs. Deficit precipitation years of 3 to 7 years duration did occur in the 1930's and 1950's, resulting in a dust bowl syndrome over vast areas of the Great Plains.

Some dry farming areas in southeastern Colorado are classified as having near-desert climates such that profitable crop production is possible only by having 2 successive years of above-average rainfall. In such cases, when rainfall returns to average or less, crop failure becomes chronic. Just because land is level and east of the Rocky Mountains does not imply that the climate at that place is suitable for sustained dryland agriculture. Some areas are too dry, too warm, and too windy too often.

Wasted Water

Water losses of natural precipitation are great. Evaporation from soil and plant surfaces alone accounts for 50 to 75 percent of all water loss in the Great Plains. It is part of the natural water cycle. Evaporation does serve a purpose in cooling effects as an air-conditioning system for plants through transpiration. Evaporation is a function of air temperature, wind velocity, and humidity. In the Great Plains, humidity is normally low, which intensifies the role of air temperature and wind velocity in evaporation losses. Evaporation losses from a free water surface at Akron are shown in figure 3. Losses exceeding one-half inch of water per day are common during the summer. These data suggest that cooling the soil slightly or reducing ground surface windspeeds by any means will significantly reduce evaporation losses and thereby conserve water.

Torrential summer rains common to the Great Plains produce uncontrolled water runoff. Frozen

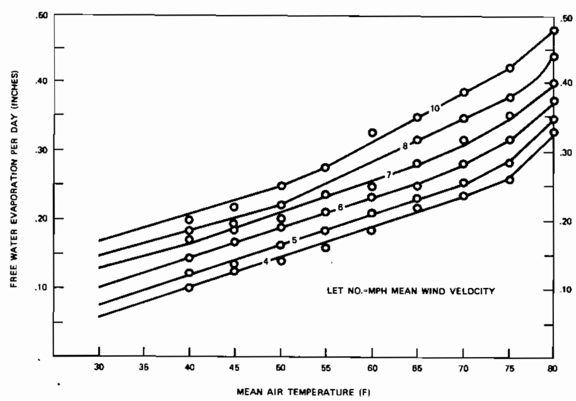

FIGURE 3.—Free water evaporation per day as influenced by air temperature and wind velocity, Akron, Colo., 1911-66 (*16*).

soils prevent snowmelt intake. Blizzards stockpile snow in the wrong places. Hailstones pulverize crops and occasionally float to the end of the field after the damage is done. The morning dew is gone shortly after sunrise. Much water evaporation occurs when center pivot, overhead irrigation systems disperse water into the air on hot, windy afternoons. Irrigation water may percolate beyond the root zone of growing crops. Weed growth alone consumes an estimated 7 to 9 million acre-feet of water per season on Great Plains wheatfields. This volume nearly equals the entire irrigation allotment from the Colorado River system, the lifeline of several Southwestern States.

These sources of wasted water are imposing and perhaps discouraging. Yet dryland and irrigated agriculture in the west-central Great Plains has survived trial and error and is presently thriving, thanks to recent water conservation innovations. These innovations are based on research and experience and are designed to enhance soil water intake, storage, and utilization.

II. STRATEGIES FOR WATER INTAKE EFFICIENCY

This section will discuss a series of established findings and new techniques for increasing the percentage of soil water intake for improved crop growth regardless of normal or less than normal rainfall conditions. Considerable progress has been made in this field during the last 25 years.

Summer Fallow

Fallowing for wheat represents the single most important cultural crop system in semiarid regions of the Western United States (*27*). It is now used on 8.7 million acres in the west-central Great Plains and about 30 million more acres in other western wheatlands. Summer fallow was almost universally adopted in the semiarid Great Plains following the 1930's dust bowl, higher wartime prices, and much improved tractor power systems and implements needed to control weeds during fallow.

Fallowing implies deliberately extending the noncropped or dormant season between crops to accumulate sufficient soil water to reduce the risk of failure when the next crop is finally planted (*46*). For a winter wheat-fallow rotation in the central Great Plains, the fallow period is 14 months, from roughly early July harvest one year to early September planting the next. A 3-year rotation of fallow-wheat-sorghum is commonly practiced in subhumid areas of the central Great Plains. The quality of fallow systems, however, is subject to numerous climate, soil, and management factors.

The basic objectives of fallowing are to:

- Maximize soil water storage
- Maximize plant nutrient availability (nitrogen)
- Minimize soil erosion hazards
- Minimize energy and economic input

Years of research and experience suggest the following concepts for upgrading these objectives (*3, 9, 10, 11, 14, 15, 18, 23, 24, 26, 49, 50, 52, 53, 54, 55, 56*):

- Weed control for the entire 14 months of fallow
- Standing stubble overwinter to capture snow
- Straw mulches during warm season for better water intake and decreased evaporation
- Hard soil clods ½ to 3 inches in diameter for wind erosion control

Fallow systems have evolved by periodic introduction of improved equipment and new knowledge as dramatized by data shown in table 1 by 15-year periods obtained at the U.S. Central Great Plains Research Station. Categories of fallow systems included maximum tillage, conventional bare fallow, stubble mulch, minimum tillage, and projected use of no-till fallow. Fallow efficiency is defined here as the percentage of precipitation retained in the soil profile from date of wheat harvest to wheat planting 14 months later.

As fallow systems improved the capacity to retain straw mulches and control weeds more efficiently throughout the fallow season, the percentage of soil water storage gradually improved from 19 percent during 1916-30 to 33 percent during 1961-75. Improved soil water storage, in turn, helped to increase wheat yields from 15.9 bushels per acre in 1916-30 with an average 17.3 inches precipitation to 32.2 bu/acre during 1961-75 with only 15.3 inches precipitation. In fact, wheat yields at this location have averaged 35.0 bu/acre from 1968 to 1977 with an average annual precipi-

TABLE I.—*Progress in fallow systems and wheat yields, U.S. Central Great Plains Research Station, Akron, Colo.*

Years	Changes in fallow systems	Average annual precipitation	Drought years	Fallow water storage[1]	Fallow efficiency	Wheat yield	Water use efficiency[2]
		Inches	*Number*	*Inches*	*Percent*	*Bu/acre*	*Bu/acre-in*
1916-30	Maximum tillage; plow harrow (dust mulch)	17.3	1	4.0	19	15.9	0.46
1931-45	Conventional tillage; shallow disk, rod weeder	15.8	5	4.4	24	17.3	.54
1946-60	Improved conventional tillage; begin stubble mulch 1957	16.4	3	5.4	27	25.7	.78
1961-75	Stubble mulch; begin minimum tillage with herbicides (1969)	15.3	4	6.2	33	32.2	1.05
1976-90	Projected estimate. Minimum tillage; begin no-till 1983	[3]16.2	3	7.2	40	40.0	1.23

[1]Based on 14 months fallow, mid-July to second mid-September.
[2]Assuming 2 years precipitation per crop in a wheat-fallow system.
[3]Assuming average precipitation from 1976 to 1990.
Source: Adapted from Wittmus et al. (*60*).

tation level of 14.3 inches. These data clearly show that improved retention of water by strategic application of known principles of reduced evaporation and water intake by mulches plus more timely and complete weed eradication can have considerably positive impact on alleviating the effects of reduced water supply. Similar data can be cited from North Platte, Nebr., and Colby, Kans., Experiment Stations (*27*).

A review of some of the specific aspects of the fallow systems listed in table 1 follows.

Maximum tillage, as used prior to 1930, refers to fall or spring plowing succeeded by frequent harrowing (dust mulch) after each significant rain. This usually involved 7 to 10 operations per season. Although weeds were destroyed so were straw mulches and wind protective clods. Fallow efficiencies usually ranged from 14 to 22 percent.

Conventional bare fallow began about 1930 and utilized shallow disking and bare rod weeders. This system is still in vogue on 20 to 30 percent of all fallow acres today, but farmers are using better designed disks and rod weeders adapted with semichisel tongs that save straw mulch and more soil clods. This system requires five to seven operations per fallow season. Fallow efficiencies here range from 20 to 25 percent (table 1).

Stubble mulching, as developed from 1945 to 1955, is conducted by undercutting stubble with V-blades, steel bars, and duckfoot chisels. Straw mulches significantly increase fallow efficiency to levels of 27 to 33 percent as a function of mulch quantity (tables 1 and 2). Mulches facilitate soil water intake by cushioning raindrop impact and reduce evaporation potential by both cooling the soil and decreasing windspeed (fig. 3). Data obtained by D. E. Smika (personal commun.) show that upright stubble reduces evaporation more effectively than leaning stubble; leaning stubble, better than flat stubble; and flat stubble, much

TABLE 2.—*Soil water storage during fallow as influenced by straw mulch rates at 4 Great Plains locations*[1]

Location	No. of years tested	Water per tons per acre mulch			
		0[2]	1	2	3
		Inches			
Bushland, Tex.	3	2.8	3.9	3.9	4.2
Akron, Colo.	6	5.3	5.9	6.5	7.3
North Platte, Nebr.	7	6.5	7.6	8.5	9.2
Sidney, Mont.	4	2.1	2.7	3.7	4.0
Average soil water		4.2	5.0	5.7	6.2
Water gain by mulching		---	.8	1.5	2.0

[1]Data interpolated from references. (*23, 24, 50, 55, 56.*).
[2]No mulch.

better than no stubble. Some operators also undercut weeds in new wheat stubble shortly after harvest. This saves 0.5 to 1.5 inches of water per fallow season, and increases wheat yields 2 to 7 bushels per acre (*18, 50*). Stubble mulch tillage usually requires four to six operations per fallow season. Today, many operators blend disk and sweep operations to meet changes in stubble, weed, and volunteer wheat eradication conditions from season to season.

Minimum tillage (two to four operations) substitutes contact and preemergence weed control herbicides for one or more tillage operations per season (*3, 18, 53*). Fallow efficiencies with this system have ranged from 33 to 38 percent. Experimentation with herbicides began during 1948-55 with contact types and accelerated after 1962-67 with the advent of promising new contact and preemergence types such as atrazine, cyanazine, glyphosate, hexazinone, metribuzin, paraquat, and others. At present, minimum tillage is undergoing extensive field experimentation and early stages of commercial adaptation because of energy-saving potential and Environmental Protection Agency approval for use of certain herbicides. A number of plant and soil residual effects are being observed, Preemergence herbicides in fallow have proved more effective when applied in the fall on new wheat stubble with residual effects lasting well into June of the next season (*18, 53*). The emphasis is on killing all weeds, leaving stubble upright until early summer, and reducing tillage operations to an average 2.5 per season. The system has increased soil water storage an average 1.0 to 2.0 in/acre and available nitrogen an average of 20 to 30 lb/acre per fallow season at Akron above that of modified stubble mulch. These growth inputs have in turn increased the yield of wheat 4 to 13 bu/acre (*18, 53*) compared with spring-applied stubble mulch tillage.

Minimum tillage has also proved highly beneficial for water conservation, reduced wind erosion potential, and 20- to 30-percent higher yields in a fallow-wheat-sorghum rotation in Nebraska and Kansas (*53*). Present trends for shorter straw wheat varieties, higher fuel and equipment costs, improved herbicide versatility and application techniques, and higher wheat yields all indicate that minimum tillage fallow may be widely adapted commercially by 1982.

No-till farming is already being used on 10 to 15 million acres of corn in the Midwest. This involves complete substitution of all tillage (except one for seedbed preparation) with combinations of contact and preemergence herbicides. Experimentation is underway at Akron and other locations for adaptation of no-till to the semiarid fallow-wheat rotation. Problems include high cost of certain contact herbicides, possible residual carryover of preemergence herbicides in sandy or high lime soils, and drilling wheat into heavy stubble. Preliminary soil water conservation data from D. E. Smika (personal commun.) show 40- to 45-percent fallow efficiency, much above other methods. Assuming normal progress of ingenuity, this system could arrive on the commercial scene by 1985. The potential benefits are impressive: Elimination of dust bowl threats and possible wheat yields of more than 40 bu/acre compared with the current yield of 25 to 30 bu/acre under the same amount of precipitation.

Implications of new technology, including summer fallow as related to commercial wheat yields in the west-central Great Plains, will be discussed in section V.

Snow Control

Uncontrolled snow has long been the bane of the northern and central Great Plains. Violent storms disrupt communications and transportation and threaten death and injury to human life, livestock, and wildlife. Yet, in favorable seasons, snowfall is a valuable water resource for range grasses, cropland, and recharge of ground water (*1, 4, 19, 20, 25, 52, 58, 59*).

What knowledge we have concerning snow in the Great Plains is minimal and only recently acquired. An estimated 24-million acre-feet of water per year from snowfall is received in the northern Great Plains alone (*8*). Few estimates exist regarding snow water losses to evaporation, sublimation, runoff, drifting onto nonuse sites, and deep percolation in creek bottoms or below root zones of grasses and crops.

During 21 winter seasons at Akron, snowfall averaged 32 inches deposit with 3.8 inches water content per winter. Seasonal variations ranged from 11 to 82 inches. These values are typical of the area from the 38½° parallel north to the

Canadian border. South of this line, snowfall expectancy diminishes rapidly.

When effectively placed, snowmelt is a much more efficient source of soil water than rain. Tests (*20*) have shown water storage from snow at 53 percent of total snowfall precipitation in large fields of undisturbed wheat stubble, 75 to 100 percent in wheat stubble on wind transport receiving areas (north edges 100 ft wide), 38 percent in ungrazed native grass, and 64 to 70 percent in captured snowdrifts. On the other hand, rainfall recharge on open soil has averaged 25 to 30 percent during spring months, 0 to 10 percent in the summer, and 20 to 25 percent during early fall. Snowmelt water contributes about 45 percent to the area's wheat production in fallow-wheat rotations north of U.S. Highway I-70 (*20*).

Snowdrift manipulations with narrow rows of vegetative barriers and with wood-slat fences offer some water conservation potential for crop production and shelterbelt establishment (*25*). Highlights of these two snow control ideas are given below.

Vegetative Barriers

Vegetative barriers are living snow fences whereby blowing snow is deposited leeward 12 to 15 times the height of the fence onto a designated target crop area. Desired barrier characteristics include (1) narrow double rows as insurance against wind gaps; (2) 1½- to 4-ft-tall, flexible stalks to eliminate breakage; and (3) stalk populations to provide 65- to 75-percent air porosity. This involves parallel strips spaced 30 to 60 feet apart and generally oriented east-west—perpendicular to storm winds. Leeward of barriers, windspeeds are reduced 80, 60, 40, and 30 percent at distances of 2, 5, 8, and 11 times the height of the barrier, respectively (*1, 4, 25*).

Tall wheatgrass seems to be the best barrier for trapping snow that would otherwise blow off dryland crop areas. Since 1959, researchers (*25*) have evaluated other vegetative barriers and concluded that crop stubble, such as sorghum and sudangrass, also successfully traps snow but requires annual installation. Trees and bushes in the semiarid central Great Plains are not good field barriers as they sap soil water for distances up to four times their height and take years to establish (*21*).

Tests at Akron showed sudangrass barriers increased soil water storage overwinter an average of 1.5 inches and increased wheat yields 4.0 bu/acre. This excluded 10 percent of yield because of land space occupied by the barrier strips (*35*). From 1974 to 1977, tall wheatgrass barriers trapped 10.8 inches of tightly packed drift snow containing nearly 3 inches of water per season (table 3, fig. 4). About 1.9 inches of snowmelt infiltrated the soil, which increased dry matter forage yields of rye, wheat, hay millet, and sudangrass 1,065 lb/acre per season.

Vegetative barriers do more than deposit snow. Crops and soils are protected from drying winds and wind erosion damage. Drawbacks to barriers

TABLE 3.—*Yield of continuously grown forage crops*[1] *by years involving tall wheatgrass snow barriers versus no barrier and fallow, Akron, Colo.*

Crop year	Yield with no barrier	Snow-melt water[2]	Yield of barrier area[3]	Yield gain in barrier area	Snow-melt yield effic.	Fallow crop[4]
	Lb/acre	*Inches*	*Lb/acre*	*Lb/acre*	*Lb/acre-in*	*Lb/acre*
1974	2,480	0.95	2,840	360	380	4,570
1975	2,975	1.85	3,595	620	335	5,490
1976	2,100	2.25	3.710	1,610	715	4,020
1977	2,365	2.68	4,035	1,670	625	5,245
Average	2,480	1.93	3,545	1,065	550	4,830

[1]Combined dry matter yield of winter rye, winter wheat, sudangrass, and hay millet.

[2]Gain water in barrier area.

[3]Yields were reduced 10 percent to compensate for land area occupied by grass barriers.

[4]One crop per 2 years; average annual yield = 2,415 lb/acre.

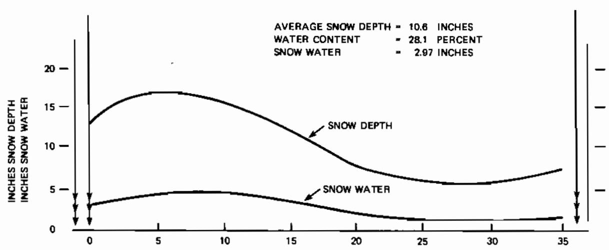

FIGURE 4.—Snow depth profile between tall wheatgrass barriers resulting from one major snowstorm per season, Akron, Colo., 1974-77.

include one-direction farming parallel to the strips, and also, during and after strip establishment, the grass barriers must be sprayed periodically for weed control.

Grass barriers could be used for quick farmstead protection, as a medium for shelterbelt plantings, and for increased forage production where livestock is the main enterprise both on cropland and rangeland.

Artificial Fences

The standard red highway snow fence is 48 inches high with 58-percent air porosity. Experiments were conducted at Akron (*25*) with 48- and 24-inch-high fences to test air porosities of 37, 58, 69, 72, and 86 percent to change drift patterns. Fences containing 69- to 72-percent air porosity formed the most desirable snowdrifts in terms of volume and width (15 times the height of the fence) for storm conditions in northeastern Colorado (see fig. 5). In many storm situations, the standard highway fence formed drifts too close to the fence.

Fences, 24 inches high, deposited 70 percent as much snow as fences 48 inches high. Snowmelt efficiency in soil on target area deposits averaged 68 percent regardless of snow depth distribution (*25*).

In another test, a 72-percent air porosity snow fence was used to increase yields of crested wheatgrass, intermediate wheatgrass, and Russian wildrye an average 500 lb/acre of dry forage to a distance of 55 feet leeward of the fence compared with nontarget grasses (*25*). This fence porosity is achieved by removal of every third wood slat of a standard highway fence. This system could also be used to accumulate soil water storage for one or two seasons in advance of planting two-row shelterbelts.

In conclusion, the use of snow as a water resource needs to be extended beyond western mountain watersheds if future water demands are to be met.

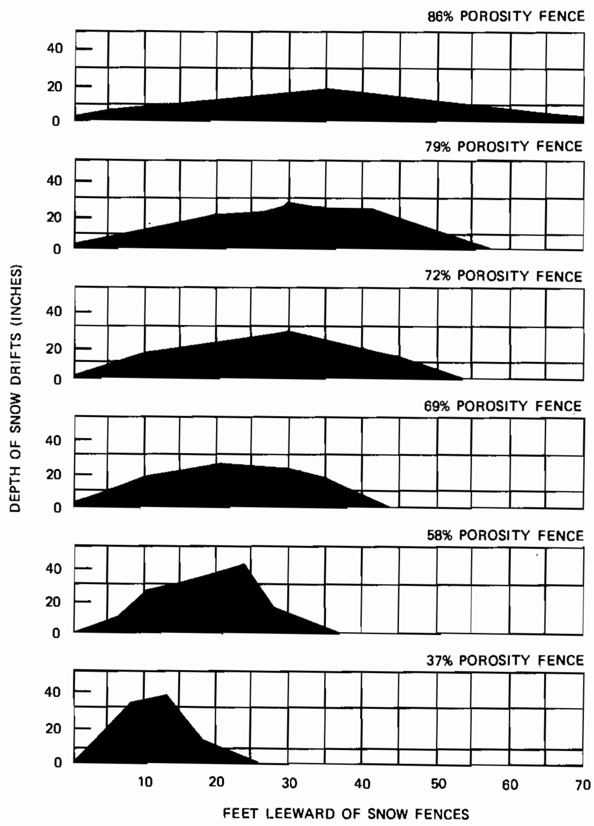

FIGURE 5.—Influence of snowfence porosity on drift deposits. Typical snow accumulation resulting from 30-mile-per-hour wind with 6 inches of dry snow, Akron, Colo. (*22*).

Runoff Water Control

In the northern Great Plains and upper Midwest, rapid snowmelt on frozen soil is a major flood hazard and results in the loss of much valuable water (*59*), whereas heavy spring rains and summer thunderstorms induce runoff in the central and southern Great Plains. Estimates of runoff range from 0.25 inch to 2 inches/acre per season on given land sites. Avalanching of water down long slopes is also very erosive.

Controlling runoff requires engineering and agronomic systems. Some methods include (1) subdividing larger fields to reduce water avalanching, (2) using straw mulches to soften raindrop impact and speed water intake, (3) chiseling up soil clods to act as miniature dams, (4) planting furrows on the contour, (5) strip cropping, (6) grassing waterways, and, sometimes, (7) recommending no farming at all if slopes and erosiveness are prohibitive.

Use of engineering systems to control water implies earth moving of some kind. Land leveling, lagoon enlargement, waterway flood pans, and terraces have all shown promise in water control (*35, 36, 37, 39, 40, 65*). In most cases, there is a trade-off between earth moving costs and exposure of less fertile subsoil as weighed against better water utilization and higher crop yields.

Land Leveling

Land leveling is a technique generally used to spread water uniformly over fields and increase the time of infiltration. Leveling may frequently involve some land grading to permit uniform flow of water across a leveled field to provide drainage at nonerosive velocities. Land leveling is most commonly used with gravity irrigation systems; however, some zero-zero slope leveling has been done on dryland to eliminate runoff and to improve drainage of saline soils.

Dryland is leveled to retain all precipitation, eliminate runoff, and increase soil water storage. Research on dryland leveling at Akron has shown some promising results (*39*). Level benches without a contributing area averaged 1.7 inches more available water annually than the nonleveled area over a 5-year period. Grain sorghum was grown continuously in the level bench and on fallow in the nonleveled area. Two-year production totals were 21 bushels per acre greater in the level bench than on the nonleveled area. When both leveled and nonleveled areas were fallowed for winter wheat production, leveling increased total available water by 1.2 inches annually and yields by 3 bu/acre over the nonleveled area; however, the differences due to leveling varied with growing season precipitation from season to season. When growing season precipitation averaged 9.5 inches, leveling showed no increases in wheat yields. When the precipitation averaged about 14 inches, the leveled areas yielded 11 bu/acre more wheat than the nonleveled areas. Though dryland leveling has shown some potential for improved water management on semiarid lands, its economic feasibility is questioned because of the variability of precipitation, high cost of leveling, and fertility problems created by deep cuts and fills.

Lagoon Enlargement

Shallow lagoons are common in the Great Plains. Many are old buffalo wallows, small drainless slumps in the original landscape, or wind blowouts from former droughts. The bottom soils are mostly heavy types, such as silty clay loams and dark-colored clay loams. Soil fertility is high, being rich in nitrogen, organic matter, and phosphorus. Without treatment, lagoons flood out grain crops and are usually infested with perennial noxious plants such as silver-leaf povertyweed, field bindweed, and Canada thistle. Smaller lagoons have rounded saucer-type slopes to the bottom.

Rehabilitation of lagoons is relatively simple (*40*). Lagoons can be leveled by moving lighter textured soil from the edges of the lagoon to and across the bottom. Surface area of the leveled lagoon is more than doubled, which provides better distribution of impounded runoff and increases water intake. The ratio of contributing to leveled lagoon area should be about 3:1 and no greater than 6:1, depending upon soil type, rainfall patterns, and watershed treatment. If watersheds are too large, diversion terraces may be built to obtain the desired ratio. If needed, noxious weeds should be destroyed 1 year in advance of leveling. The system provides a semicontrolled natural irrigation for growing beneficial crops in lagoons that otherwise are useless because of excess water. The additional water received in a leveled lagoon with rich soil will usually permit continuous cropping of forage crops or high yield domestic grasses and legumes with yields more than double that around the outside fringe of the lagoon. Costs may be amortized in 4 to 6 years from the increased yield.

Waterway-Leveled Pans

As with lagoon enlargement, waterway-leveled pans are designed to utilize water runoff for crop production in semiarid areas. The system is a combination of land leveling, detention dikes, and spillways constructed in shallow, meandering natural waterways to intercept, store, and utilize the runoff that normally flows through them (fig. 6). The ratio of contributing area to leveled pan areas is dependent on the topography of the natural waterway and treatment of the watershed. Pan size and shape would depend on the width and natural slope of the waterway bottom. Detention dikes are constructed at the lower end of the pan area with a gate and spillway to control the volume of water desired for storage in the leveled area and to avoid prolonged flooding. A series of leveled pans may be constructed downslope in the same waterway whereby surplus water from an upper pan may be intercepted by a lower one. Soil water storage is increased to permit annual cropping. The supplemental runoff during the grow-

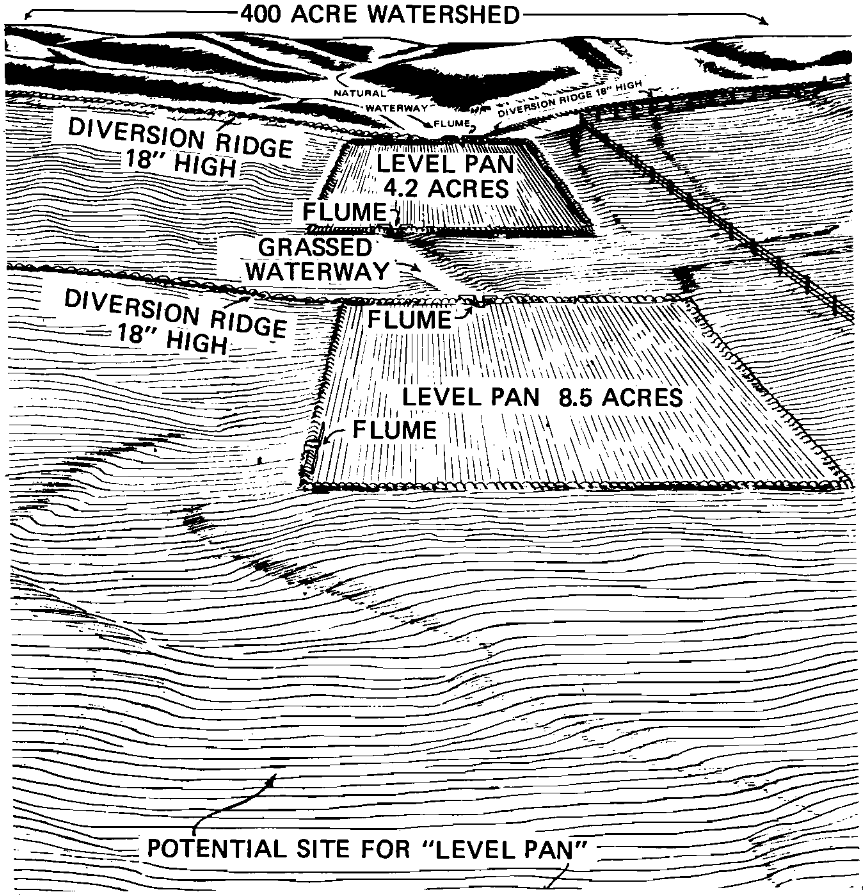

FIGURE 6.—Schematic drawing of a water-spreading system utilizing runoff from mixed cover watersheds (*22, 35, 36*).

ing season has significantly increased crop yields over that on nonleveled dryland areas. In addition to the results shown for grain and forage sorghum presented in table 4, millet, corn, alfalfa, sudangrass, and high-yield grasses have been grown with increased yields in the leveled pan system designed to use supplemental runoff for annual crop production (*35, 36, 37*).

Terrace Designs

Terraced hillsides are as old as recorded history. Remnants of elaborate terrace systems have been found in Europe, Asia, Africa, Central and South America, and the larger Indonesian islands. Most of the world's terraces were constructed at an enormous input of hand labor for the production of potatoes, rice, wheat, barley, olives, and fruit. Terraces held little interest for the mechanized American farmer until after 1940 when water erosion became a serious threat to sloping humid area farmlands. The potential of

TABLE 4.—*Yield and water use efficiency of forage and grain sorghums on level pans and check plots, Akron, Colo. (22, 35, 36)*

Plot	Stored water in 5 feet of soil at seeding	Supplemental water from runoff	Yield	Water use efficiency	Gross return per acre
	Inches	*Inches*	*Lb/acre*	*Lb/ac.·in*	*Dollars*
Grain sorghum:					
Lev. pan	8.76	±2.12	[1]2,454	163	[1]$41.70
Check	5.46	− .77	0	0	0
Forage sorghum:					
Lev. pan	7.53	±2.57	[2]41,400	[3]925	[2]82.80
Check	6.63	− .77	[2]12,800	[3]486	[2]26.60

[1]RS 610 grain sorghum. Grain sold at $1.70 per hundredweight in 1962.

[2]Green silage. FS-22 forage sorghum. Crop sold as green silage at $4/ton.

[3]Oven dry.

using various terrace designs in subhumid and semiarid lands is a recent innovation.

The original terraces were of the ridge type, constructed on the contour to control erosion. The concave channels above the ridge were level, closed-end terraces or graded to allow drainage of excess water at nonerosive velocities; however, they did not efficiently utilize the water stored in the channel and were a hindrance to farming operations. The conventional ridge-type terraces were later modified to a bench-type terrace to effectively control erosion and to provide uniform distribution and efficient utilization of the water intercepted by crops in the leveled bench (fig. 7).

have varies from 2:1 to 4:1, depending on precipitation probabilities, slope, and soil type.

Level bench systems have more than doubled the yields of forage and grain sorghum produced on the slopes (*34, 37, 65*). Results of wheat production in a crop-fallow rotation on a bench terrace system at Akron are shown in table 5. Level benches without runoff increased wheat yield 1.5 percent over that on a contributing area. Yields were increased an additional 14.8 percent by runoff impoundment in the benches. The increased water storage that occurs in bench terraces during the noncrop season has provided sufficient soil water to deter complete crop failure in years when precipitation is critically short.

ZINGG TERRACES FOR MOISTURE CONSERVATION

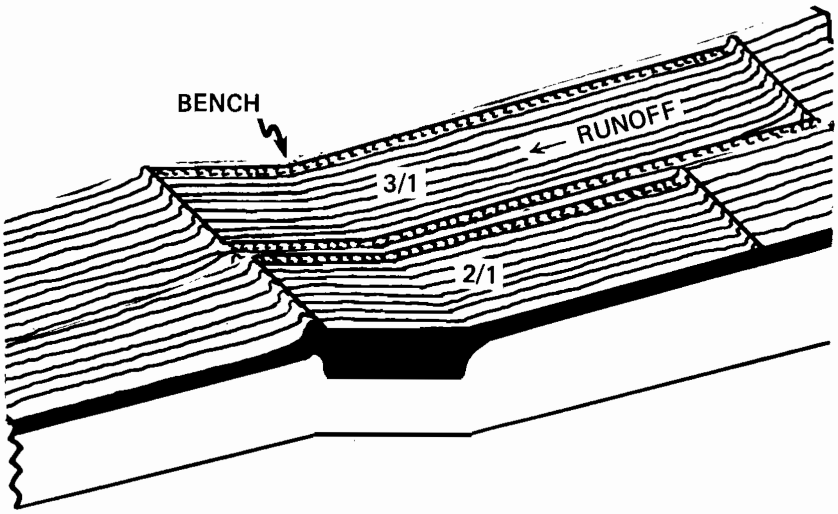

FIGURE 7.—Layout of Zingg conservation terraces and profile of the system showing twice as much water storage in the level benches (*22, 37*).

On semiarid land, the bench terraces are constructed level throughout their entire length and width because the intercepted water is seldom excessive. The leveled bench is leveled to zero grade in all directions with a wide elevated ridge on the lower side to retain the impounded water. Width of the bench is dependent on slope, but may be constructed to accommodate standard machinery widths. The interval between bench terraces also is dependent on steepness of slope and soil type and serves as a runoff contributing area for the leveled land. The system is best adapted on long uniform slopes of 1 to 5 percent and on deep soils. Construction costs become prohibitive on steep slopes. Ratios of contributing to level bench area

Water Harvesting

The ancient art of water harvesting was thought to have been first used about 4,000 years ago on desert lands to collect precipitation to irrigate cereal and vegetable crops for food supplies. The practice is used to this day in many arid and semiarid regions of the world for food production. There is evidence of similar systems being used in the southwest arid areas of the United States over 500 years ago for domestic water supplies (*41*). Recent development of water-harvesting systems began in the 1950's in the United States to provide water for livestock watering supplies (*13*). Water harvesting catchments have been con-

TABLE 5.—*Water supply and winter wheat yields on fallow in Zingg conservation bench terraces, 1972-76, Akron, Colo.*

Bench system	Runoff	Total available water	Total dry matter	Grain	Grain WUE[1]
	Inches	*Inches*	*Lb/acre*	*Bu/acre*	*Lb/ acre-in*
Contributing area (CA)	−0.6	16.7	5,690	31.7	118
Bench without CA	.0	19.1	5,300	32.2	122
Bench with CA[2]	1.8	19.4	6,120	36.4	135

[1]WUE = water use efficiency.
[2]Average of 2:1 contributing area to bench area.
Source: R. H. Mickelson, unpublished results.

structed by covering a specific site with impervious membranes or treating the water chemically or mechanically to induce runoff (*13*). More than 40 percent of the precipitation falling on some of the catchments has been collected. Impervious membranes such as concrete, sheet metal, butyl rubber, silicone, asphaltic compounds, polyethylene, and sodium carbonate are relatively efficient and durable in warm, dry climates, but have not always performed well in climates with extreme variation of temperatures (*13, 43*). In these climates, sheet metal and butyl rubber have proved to be most effective (*38, 44*). Criteria for the design and construction of water-harvesting systems have been developed for arid zone use.

Where rainfall is insufficient and soils are available, water-harvesting systems could be utilized on land in which alternate "runoff strips" are treated (surface sealed and stabilized) so as to contribute rainfall as runoff to adjacent catchment strips where crops can be grown.

Irrigation Conveyance and Scheduling

Inefficiencies in stream-fed irrigation systems are no less than those in rain-fed agriculture. Evaporation and seepage losses occur all the way from mountain snowbanks to the field many miles away. Every storage reservoir, canal, ditch, and field overrun contributes to significant nonuse and sometimes misuse of valuable water. During mountain snowmelt shortages, such as in the drought of 1977, these water losses are magnified. In recent years, trial and error plus sound engineering have reduced some of these water losses. These improvements include better streamflow forecasts; more efficient water impoundments, lined canals, and ditches; and greater understanding of crop water needs during the growing season.

Across the uplands of the Great Plains, ground water development for furrow and center pivot sprinkler irrigation began in the Texas Panhandle shortly after World War II and, since 1967, increased rapidly north along the Kansas, Colorado, Nebraska borders. Exact acreages are unknown, but estimates in 1977 include the following:

State areas	*Ground water irrigation Million acres*
Northern Texas	5.2
Western Kansas	1.8
Eastern Colorado	.6
Western Nebraska	.5
Southeast Wyoming	.2
Total	8.3

Water intake efficiencies for irrigation water, whether delivered by ditch-furrow method or by overhead sprinkler, are not unlike dryland farming. Adverse evaporation by hot dry winds, crusted soil, downslope runoff, and overuse and underuse of water at critical crop growth periods all contribute to less than optimum water utilization. An understanding of total and seasonal water requirement by various types of plants represents a serious knowledge gap for most commercial irrigators. It is almost universally agreed upon by field technicians and research scientists that the present volume of irrigation water commonly used for annual row crops such as corn, grain sorghums, and sugar beets could be reduced 20 to 30 percent with minor changes in irrigation scheduling without losing yield potential (*28, 29, 31*).

Dormant Season Irrigation

The best place to store water is in the soil itself. This viewpoint involves three aspects for maximizing water intake and later utilization by crops as follows: (1) The best efficiency of water use is achieved when the crop root zone is water filled at seeding time; (2) the best time to fill the root zone is during the cool noncrop dormant season, sometimes months in advance; and (3) the best way to assist water intake and reduce evaporation, according to R. W. Shawcroft (personal commun.), is to provide 2 to 5 tons/acre of crop residue, such as straw and stalks. These concepts probably apply more to ground water than stream-fed irrigation. River water is usually not available until snowmelt runoff is discharged in late May and early June.

A simple guide for preirrigation is shown in table 6. For some crops—such as winter wheat, millet, spring barley, and beans—full production on heavy and medium textured soils can be achieved by adding small amounts of irrigation water beyond that required of a full soil profile at seeding time. This is based on total water requirement for those crops and the expectancy of some natural rainfall during the growing season.

TABLE 6.—*A guide for preirrigation water requirement to fill the root feeding zone of commercial crops in various soils*

Crop	Soil watering depth	Water required for the following soil texture types[1,2]		
		Heavy	Medium	Light
	Feet	*Inches*		
Alfalfa	>7	18	14	8 to 10
Sugar beets	6	13	11	6 to 8
Winter wheat	6	13	11	6 to 8
Corn, grain sorghum	4½	9	7	4 to 6
Millet, barley	3½	7	6	3 to 4
Dry beans	3	6	5	3

[1]Based on soil water holding capacity as follows:

Heavy:	Clay loam, silty clay loam	= 2.5 in/ft
Medium:	Loam and silt loams	= 2.0 in/ft
Light:	Sandy loam	= 1.5 in/ft
Light:	Loamy sand	= 1.0 in/ft

[2]Assuming the soil already contains 1 to 3 inches residual water to rooting depth.

Dormant-season irrigation significantly reduces evaporation potential compared with light and medium irrigations during the growing season. Second, a reserve of soil water greatly reduces the high energy cost requirements of continuous crop season pumping. Third, a reserve of soil water is good insurance in case of pump breakdown. Crop failures and near crop failures often result because of pumping malfunctions at critical stages of crop growth. Lastly, this author has observed center pivot systems that could not deliver overhead water as fast as the crop consumed the water, resulting in periodic crop leaf wilting. For corn and sugar beets, such a water deficit can be disastrous. Again, reserve soil water in the root zone eliminates this hazard.

Crop Season Sprinkler Irrigation

There is an evaporation demand per day from all fields based on airborne water delivery plus soil and plant surfaces (*28, 29*). Evaporation demand greatly increases with low humidity, higher wind velocity, and high temperatures (*16*). The implications of evaporation demand with sprinkler irrigation are as follows:

Type system	Nozzle delivery	Evaporation demand	Net water for crops
	Inches		
A	1.2	0.3	0.9
B	.9	.3	.6
C	.6	.3	.3
D	1.5	.5	1.0
E	1.0	.5	.5

We see that system A pumps twice as much water in 48 hours as system C, but the net value is three times greater. System D delivers 50 percent more airborne water than system E but 100 percent more net water for crops. Thus, a greater volume of water delivered less often is more efficient than the same volume spread over a longer period. Similarly, in cases of single flood irrigation, it is usually more efficient to concentrate the water on smaller areas than to spread it over too large an area. Additional information regarding irrigation and water stress can be obtained from Heermann et al. (*31*), Hanks et al. (*28, 29*), and Shawcroft et al. (*46, 47*). Future ground water depletions over several million acres combined with fast rising pumping costs will necessitate a much improved irrigation efficiency over that being practiced today.

Deep Plowing—a Special Problem

Deep plowing is a one-shot treatment that can be used to dilute and break up thin layers of impervious clay and hardpans that are shallow in the soil profile. In this manner, water infiltrates the soil faster and is less exposed to evaporation losses thereby increasing water efficiency, drought or no drought. Most previous deep plowing experiments have occurred where water is plentiful by irrigation or natural rainfall. Deep plowing at Akron represents one attempt of this type in a semiarid environment (*17*). The Weld silt loam, a benchmark soil of the west Central Plains that covers several hundred thousand acres, contains a thin genetic B_{21}clay layer 4 inches thick. Deep plowing to 17 inches as a dilution technique improved soil water intake.

The results of this plowing experiment proved positive even for dryland conditions (table 7). Although not shown, wheat straw mulch applied at rates of 1 to 2 tons/acre saved an additional 0.8 inch of soil water per fallow season above that gained by deep plowing. Thus, deep plow plus mulch saved 1.6 inches more soil water than shallow plow without mulch. This increased grain yields an average of 7.7 bu/acre and total dry matter by 1,385 lb/acre, which equals 885 lb/acre-in of extra stored water. These results suggest that dryland conservation practices can be additive in benefits.

TABLE 7.—*Deep plow versus shallow plow of native sod of a Weld silt loam on water storage in fallow and resultant crop yields. Plowing conducted May 7, 1967, Akron, Colo.*

Year	Available soil water at seeding		Type crop	Crop yield[1]	
	Deep plow	Shallow plow		Deep plow	Shallow plow
	Inches	*Inches*		*Bu/acre*	*Bu/acre*
1967	4.53	3.86	Millet	[2]2,830	[2]2,290
1968	7.33	5.96	Barley	27.3	19.5
1969	7.46	6.82	Wheat	26.1	21.9
1970	5.94	5.11	--do--	36.4	31.1
1971	7.26	6.63	--do--	23.3	21.9
Water or grain average	6.50	5.68		28.3	23.6

[1]Average total dry matter production, 1967-71: Deep plow = 4,845 lb/acre; shallow plow = 4,160 lb/acre.
[2]Lb/acre dry matter.

III. STRATEGIES FOR WATER USE EFFICIENCY BY PLANTS

Section II discussed a number of systems and concepts to use in upgrading soil water intake whether water availability was marginal or normal and whether from rain or irrigation. It is equally important to improve plant systems that will increase production per unit of water available. A series of water use efficiency ideas and experimental results are given in this section.

Soil Fertility

Viets (*63*) expressed a well-known axiom regarding the role of soil fertility in water use: "A plant can be using water even though it is not growing or growing more slowly because of lack of nutrients to produce new growth. Suffice it to say here that recommended use of fertilizer (where needed and properly applied) is the cheapest and most profitable way of increasing crop water-use efficiency."

A simple example of increasing water use efficiency with fertilization is given in table 8. In this case, the addition of 50 lb/acre of nitrogen increased the average water use efficiency of three grass species from 185 lb/acre-in to 305 lb/acre-in equal to a factor of 1.65 as compared with 0 lb/acre of nitrogen (*25*). Individually, the water use efficiency of Russian wildrye at 0 rate of nitrogen averaged 135 lb/acre-in compared with crested wheatgrass at 50 lb rate of nitrogen with a water use efficiency of 395 or a factor of 2.92 greater. This demonstrates, quite dramatically, the value of integrating plant species selection and fertility levels for maximum production where water supplies are sparse.

In the central Great Plains, most noneroded loams, silt loams, and clay loams are fertile with a moderate-to-good reservoir of organically bound nitrogen plus mineral phosphorus and potash. These nutrients are concentrated in the top 12 inches of soil. Continued soil erosion and crop consumption in the near future may reduce these nutrient reserves to deficiency levels in relation to water supply. This has already occurred on sandy lands and hillside slopes of heavier textured lands. Some conservationsists feel that por-

TABLE 8.—*Water use efficiency as influenced by grass species and rates of nitrogen fertilizer, 1966-69, Akron, Colo.* (25)

Species	Nitrogen rates	Water use	Yield grass	Water use efficiency
	Lb/acre	*Inches*	*Lb/acre*	*Lb/acre-in*
Russian wildrye	0	6.28	850	135
	25	7.64	1,380	180
	50	6.33	1,645	260
Average		6.75	1,290	190
Intermediate wheatgrass	0	7.36	1,270	170
	25	7.32	1,800	245
	50	7.60	2,025	265
Average		7.43	1,700	225
Crested wheatgrass	0	6.21	1,570	255
	25	6.25	1,985	320
	50	6.16	2,430	395
Average		6.21	1,995	325
All grasses	0	6.62	1,230	185
	25	7.07	1,720	250
	50	6.70	2,035	305

tions of the Great Plains have already lost more pounds of plant nutrients in duststorms than has been shipped to the elevator in the form of harvested grain. With increasing costs of fertilizer, it seems prudent to save fertile soil by simple conservation measures.

Genetic Engineering

A recent world renowned classic of genetic ingenuity was the development of short-straw small grains, particularly rice and wheat. In a way, this made tall corn obsolete. The reason is simple: Tall straw or stalks consume too much water in relation to the amount of grain produced. Energy and water are used better when the stalk is subdivided into three shorter stems with three grain heads than into a pair of taller stems with two grain heads. The grain yield potential for the same expenditure of water is thus increased 25 to 33 percent. An example of breeding shorter straw into winter wheat with resultant grain yield increase follows:

Wheat cultivars	Water use	Grain	Straw	Total dry matter
	Inches	*Bu/acre*	*Lb/acre*	*Lb/acre*
Old tall cultivars[1]	16.0	24	3,600	5,040
New shorter cultivars[2]	16.0	30	3,240	5,040

[1]Tenmark, Nebred, Cheyenne.
[2]Scout 66, Centurk, Lindon, Vona.

The historical introduction of winter wheat cultivars and relative yield capacity data as supplied by G. O. Hinze (personal commun.) is shown in table 9. The genetic combinations used for modern wheat varieties is indeed a "green revolution." Lastly, not enough credit has been given to the development of early maturing varieties that reduce time of field exposure to hail, hot wind damage, and lodging.

Some scientists fear that wheat straw can be bred too short, thus reducing both snow catchment capability and straw for mulching and wind erosion protection. Perhaps a compromise in the

TABLE 9.—*Relative yield capacity of winter wheat varieties, U.S. Central Great Plains Research Station*[1]

Wheat variety[2]	Year introduced	Relative yield capacity	Characteristics sought
		Percent	
Kharkof	1916	[3]87	Bred from Turkey Red.
Cheyenne	1931	[4]84	Winter hardiness, quality.
Comanche	1943	[4]89	Early maturity, quality.
Pawnee	1943	[4]91	Resistance to Hessian fly and loose smut.
Wichita	1945	[3]85	Early maturity, test weight.
Warrior	1963	[3]92	Quality (first variety for continuous mix).
Scout	1965	[3]98	Yield quality, some rust resistance, early maturity.
Centurk	1973	100	Quality, yield, stem rust resistance.
Lindon	1976	[3]99	Yield, quality, lodging resistance.
Vona	1977	[3]107	Do.

[1]From G. O. Hinze, Central Great Plains Station, Akron, Colo.
[2]Most winter wheat breeding began with Turkey Red, introduced in 1909, as the original parent variety.
[3]As a percentage of Wichita.
[4]As a percentage of Centurk.

future will include limited shortness of straw in combination with minimum or no-till fallow.

In a public speech made many years ago, I remarked that the ultimate goal of plant breeders and agronomists is "to grow 40 bu/acre wheat on dry bedrock." In view of 5,000 years of land erosion, population explosions, and projected fossil fuel limitations, this remark may not be as whimsical tomorrow as it seems today.

Matching Crops with Water Supply and Temperatures

Crops do not vary much in daily water requirements during their respective growing season, but peak demand can be double the average daily use (*63*). They do vary in length of growing season, which leads to a difference in total demand. Sugar beets and alfalfa have long growing seasons, requiring a high seasonal water demand, and are poorly adapted for dryland. Various crops also have peak growth periods at different times of the year. For example, fall-planted small grains, such as winter rye, winter wheat, and winter barley, have a peak demand from mid-May to mid-June. These crops can be successfully grown in many of the drier portions of the Great Plains because they can take advantage of stored soil water accumulated in fallow to carry them over a low demand winter succeeded by peak spring rainfall to match peak growth demands. Corn and sorghum, on the other hand, have peak demands in August when rainfall is more erratic and evaporation rates are high. Very little dryland corn or grain sorghum is grown where annual precipitation is less than 19 inches/year except on sandy soil with a high water intake capacity.

A short season crop, such as proso millet, has a number of advantages in utilizing minimal water. Maximum water demand for proso millet is only 12 to 14 inches compared with 16 to 18 inches for winter wheat, 20 to 22 inches for corn and grain sorghum, and 24 inches for alfalfa. Secondly, proso millet has a very low straw-grain ratio of 1.1/1 as compared with 1.7/1 for modern wheat varieties, and over 2/1 for dryland corn and sorghum. Field results at Akron show that the zero point of grain production for proso millet is 5.5 to 6.0 compared with 8.5 to 9.0 inches for winter wheat and 9 to 10 inches for grain sorghums (*27*). In many of the cool, drier, semiarid regions of the world, proso millet would be a logical substitute for barley or wheat in upgrading food production per unit of water available.

Too much or too little heat radiation dictates crop adaptation as well as water supply. In the central Great Plains, winter wheat is successful because grain maturity in late June is usually several days before hot, lethal winds occur. Spring plantings of barley and oats, on the other hand, are too late, resulting in heat blast during flowering and shriveling of grain. Above a 4,000-foot elevation, it is consistently too cold at night and usually too dry for grain sorghums in the west-central Great Plains (*27*).

Cultural Manipulations

We have discussed summer fallow, straw mulches, weed control, runoff water capture, crop selection, genetic engineering, soil fertility, and water drought escape mechanisms. Other common cultural practices are listed below:

- Reducing crop populations to match water supply, thus assuring some grain production. This method was practiced by Southwest Indians for hundreds of years. It still works.
- Wider row spacing to prolong root extension into untapped stored soil water. This practice delays drought stress until rain arrives (*22*).
- Using preemergence herbicides for summer crops such as millet and wide-row, low populations of corn and sorghums. There is little point in growing 800 lb/acre of weed tissue to compete with a struggling crop. Each pound of weed tissue reduces the yield of the desired dryland crop by about 2 pounds whether the weed grows during the dormant season (harvest to planting) or during the crop season (*18*).
- Contour cropping to slope. Drill furrows can act as little dams for water or snow catchment.
- Deep furrow drilling for small grains to provide a better microclimate, thus reducing winter kill and protecting plant crowns from wind and soil blast.
- Changing dates of seeding to better fit a given climatic regime. Earlier seedings of new varieties of millet, corn, and sorghum have produced favorable success. Fall seedings of winter wheat in late September instead of late August

are sometimes desirable to delay soil water exhaustion until spring rains arrive.

Recent exotic experimental cultural practices have produced both positive and negative results. Chemicals have been sprayed on plant leaves to promote stomatic closure and therefore reduce transpiration (*63*). Unfortunately, chemical films also inhibit absorption of carbon dioxide through the leaves at the same time. Not much gain here unless a cheap film could stop all transpiration during a drought stress that would wash off only when a significant rain occurs. In most cases, the damage is already done.

Black polyethylene films applied between plant rows have doubled water use efficiency by eliminating evaporation (*63*) and warming surface soils 5° to 7°F, which speeds up plant growth and also generates more available soil nitrogen by accelerating organic matter decomposition (*2*). However, plastic films are (1) expensive, and labor intensive for field installation, (2) can be damaged by hail, (3) a nuisance to retrieve from the field before harvest, and (4) are difficult to store for later use. Plastic films are all right for backyard gardens but not for commercial dryland agriculture.

Microslopes between wide rows and microwater runoff shields of metal, cement, butyl rubber, and plywood have been attempted with mixed success in relation to cost input (*38, 63*). Vertical reflective shields have also been used to generate heat. Again, these systems indicate gardening.

Deep Water Percolation

In the northern Great Plains, summer fallow has proved negative if sustained for too many years. Spring wheat, as grown there, has an effective root system of only 36 to 42 inches compared with 72 inches or more for winter wheat grown in the central Great Plains (*27*). Surplus water below 40 inches in these spring wheat fields begins to percolate down to an impervious layer and then migrates downslope to pop out as saline seeps complete with with creeklets and cattails. Less use of fallow is now recommended outside the seep area with deeper rooted crops such as alfalfa and domestic grasses planted near the seeps to consume surplus water.

Deep percolation is not a serious problem in the central Great Plains except on irrigated sandylands. Over-irrigation has been known to flush out substantial quantities of fertilizer nitrogen in addition to wasted water (*51*). Nitrate nitrogen pollution can occur if the surplus water migrates to nearby streambeds. Monitoring of soil water profiles throughout the growing season is now becoming more popular as a means of improving water use in these porous soils.

In dryland, deep percolation occurs largely in gravelly drainage bottoms during torrential rains or rapid melt of occasional heavy snowpack. This is positive because most of this percolation feeds underground aquifers with water slowly migrating east to northeast within the Ogallala formation or stockpiling in place with other deep geologic formations. Eventually, this water is recycled by stock wells, domestic rural use and community use, and massive ground water irrigation developments when the aquifer is large enough. Drawdown of these aquifers involves a price, especially when water is being pumped at 8 to 10 times the recharge rate. Declining water tables have already occurred with costly repercussions in large areas of northern Texas, southwest Kansas, parts of eastern New Mexico, and marginal aquifers in Colorado.

Irrigation for Best Crop Response

Earlier, we discussed irrigation scheduling primarily from the standpoint of water intake efficiency. Assuming the acceptance of a full soil profile of water at seeding time to the expected rooting depth of various types of crops, some of the high water demand crops, such as alfalfa, sugar beets, corn, and grain sorghums, will still need supplemental water during the growing season. The question is how much water and when is the best time to apply it for maximum plant elongation, early tasseling, flowering, and grain filling?

According to R. W. Shawcroft (personal commun.), corn requires 22 inches total water demand for 150 bu/acre. A full soil profile of corn on medium texture soil contains 7 inches of available water (see table 6) at planting time. Let the expectancy of seasonal rainfall from planting to grain filling be 8 inches with half being lost by evaporation. We now need 11 more inches of water to fulfill the total water demand. As previously pointed out, some irrigation water is lost by evaporation. We probably should plan on adding 15 inches of water by irrigation from planting to grain filling in 90 days. Assuming a center pivot sprinkler delivery of 1 inch per 48 hours, then a total of 30 days irrigation is required. Research by R. W. Shawcroft (personal commun.) indicates most of this water be concentrated during tasseling time and again during early grain filling for maximum efficiency.

For grain sorghum with a similar total water demand for high yields, R. W. Shawcroft (personal commun.) suggests most of the water be applied before and shortly after head emergence from the boot. Winter wheat reaches peak demand from the boot stage to soft dough. Millet requires only about 2 inches of supplemental water during head emergence to dramatically boost yields.

Let the irrigator not forget the four stages of water calculations: (1) How much comes out of the well? (2) How much comes out of the nozzle? (3) How much hits the crop and gets into the soil? and (4) How much does the crop consume above evaporation losses? Water transpiring through the plant in many commercial fields is probably no more than 40 to 50 percent of that which began at the well. All these considerations are necessary if we are to maximize water use efficiency and reduce energy and cost expenditures.

IV. STRATEGIES FOR EROSION CONTROL

Wind Control Systems

The duststorms in the western sections of the central and southern Great Plains are world famous in the same vein as cold winters in the Yukon. Duststorms are synonymous with prolonged drought. The dimensions of superstorms of the 1930's and 1950's are sometimes forgotten. Austin Zingg (personal commun., Mar. 1954) estimated that the February 19, 1954, storm of eastern Colorado and western Kansas airlifted sufficient soil to cover 480,000 acres 2 inches deep. The storm of February 23, 1977, also of eastern Colorado and western Kansas carried a huge dust cloud all across southeastern United States and 500 miles into the Atlantic Ocean off the coast of South Carolina.

Soil erosion by wind is determined by wind velocity, surface soil water, degree of soil cloddiness and surface roughness, field length along the direction of the wind, and vegetative cover on the field (*62*).

Soil is most susceptible to erosion during the dormant season after wheat has been planted, not during the fallow season itself (*27*). The risk is intensified with poor wheat stands. Soil water shortages in the fall result in winterkill of the remaining plants, thereby depriving the soil of the anchorage of healthy plants. The peak danger period is from February 10 to April 20 when small soil aggregates have been pulverized by alternate freezing, and thawing and windstorm probabilities are high. Figure 8 shows that the wind erosion potential increases rapidly with increasing severity of climate. The relative erosion hazard index at North Platte is 45 and increases south-southwest to an erosion index of 200 near Springfield, Colo.

Data comparing wind erodibility of stubble-mulch fallow and clean fallow are not extensive.

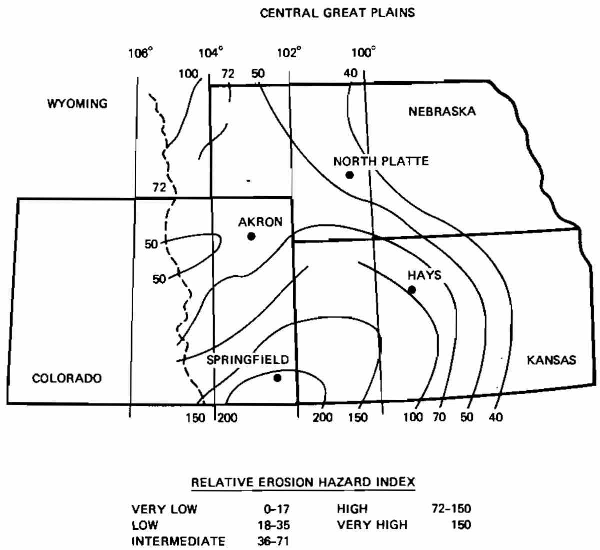

FIGURE 8.—Relative wind erosion hazard in the central Great Plains excluding the Rocky Mountains (*6*).

Some results of 8 years evaluation of tillage practices for wheat-fallow rotations in western Nebraska have shown relative wind erodibilities of one-way disk and clean tillage to be 63 and 140 percent greater, respectively, than stubble-mulch tillage (*10*). Wind tunnel tests on farmers' fields in western Nebraska in 1957 clearly demonstrate the superiority of stubble-mulch over clean fallow for wind erosion control (table 10). Of particular interest was the remarkable reduction on wind erosion potential when straw mulch exceeded 1,000 lb/acre. The data also reflect much greater erodibility for the sandy loam as compared with the heavier loam soil.

TABLE 10.—*Effectiveness of stubble mulch and clean fallow in controlling wind erosion in western Nebraska, 1957*[1]

Soil type	Kind of fallow[2]	Wind erodibility[3]	Straw mulch
		Tons/acre	*Lb/acre*
Keith loam	Stubble mulch	0.4	1,370
Do.	Clean fallow	9.8	425
Very fine sandy loam	Stubble mulch	.3	3,645
Do.	Clean fallow	16.5	800
Rosebud, very fine sandy loam	Stubble mulch	2.3	1,680
Do.	Clean fallow	22.7	480
Keith loam	Stubble mulch	.1	3,780
Do.	Clean fallow	1.8	735

[1]Chepill, W. S., and N. P. Woodruff. Wind Erosion Research Laboratory Annual Research Report. U.S. Dept. Agr., Agr. Res. Serv. Manhattan, Kans. 1957.

[2]Stubble mulch tillage accomplished with 30-inch sweeps as required to control weeds. Clean fallow accomplished by chopping stubble, plowing 6 inches deep, chiseling, springtoothing twice, and rodweeding twice.

[3]Portable tunnel data adjusted to annual soil loss for field 160 rods long.

Zingg (*64*) reported that wind erosion from certain kinds of poor fallow could be four times greater than that from continuous wheat; but the same study showed that the relative erodibility of continuous wheat was 10 times greater than that from good stubble-mulch fallow accomplished with modern stubble undercutting implements such as large sweeps and rod weeders with semichisels attached.

Erosion by wind can be controlled by any or all four principles of control, namely: (1) Produce or bring to the soil surface aggregates or hard clods large enough (½- to 3-inch diameter) to resist wind force; (2) roughen the land surface to reduce windspeed impact by implement furrows; (3) reduce field width by strip cropping or by establishing vegetative barriers, thereby reducing windspeed and soil avalanching; and, most importantly, (4) establish and maintain vegetative cover in excess of 1,200 lb/acre to protect the soil (*27, 62*).

With today's information and equipment, there is little reason for wind erosion to occur if sufficient protective vegetative cover can be produced; however, in certain areas, such as in portions of southeastern Colorado and the adjacent fringe of southwest Kansas, which average 42 to 47 percent abandonment of wheat (*27*), wind erosion poses a dilemma. Better farming practices would likely reduce crop abandonment, but whether this would be sufficient to upgrade this area to a permanent plus-side economy remains doubtful considering present wheat prices. Past history seems to offer conclusive evidence against continued dry farming of some of these lands, because of marginal climate.

Water Control Systems

Water erosion has not been a consistent major problem in semiarid areas of the central Great Plains (*27*). Major factors affecting water erosion are climate, soil types, vegetative cover, and topography. As would be expected, the major hazard involves clean fallow on sloping land during torrential rain. Strategies for reducing runoff and utilizing runoff water were discussed in section II. In general, similar strategies to control wind erosion also apply for water by (1) absorbing energy of raindrop impact with vegetative cover and hard soil clods; (2) retarding erosion by decreasing water velocity; (3) physically restraining soil movement with surface roughness; and (4) reducing length of downslope runs with interception terraces, land leveling, or strip cropping. Snowmelt runoff rarely occurs in the west-central Great Plains (*20*).

V. IMPACT OF DROUGHT ON WINTER WHEAT YIELDS IN THE WEST-CENTRAL GREAT PLAINS

One irony of the great drought of 1977 was that overall agricultural production in United States, including the Great Plains, was little diminished. Record or near record national production continued for corn at 6.3 billion bushels, wheat at 2.0 billion bushels, soybeans at 1.7 billion bushels, and grain sorghum at 0.8 billion bushels (*7, 32, 42*). For much of the concentrated grain lands, timely spring and summer rainfall alleviated the 1976-77 winter precipitation drought. Fortunately, in the United States, geographic and climatic diversity tend to smooth out the ups and downs from one major production region to another. Considering the Pacific Northwest, three distinct Great Plains regions, two divisions of the Midwest, and the southeastern region, the probability is low that more than two or three of these regions will experience severe drought during any given timespan. Secondly, some strategies for drought are being adapted into the commercial agricultural system.

Evidence of technical progress in dryland wheat production under semiarid conditions at the U.S. Central Great Plains Research Station was presented in table 1. On a mass commercial basis, the data are equally impressive as given in figures 9, 10, and 11 and tables 11 and 12. These data were compiled by the author from the Crop Reporting Services of Colorado, Kansas, and Nebraska and involved 58 major dryland wheat producing counties (*7, 32, 42*). Irrigated wheat acres and yields are not included. The dryland

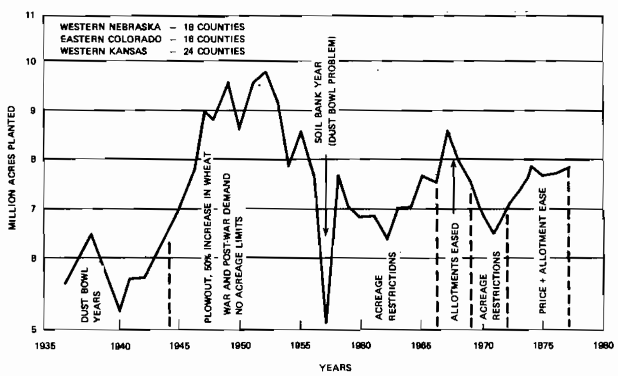

FIGURE 9.—Historical wheat acres planted in the summer fallow area, central Great Plains, 1936-77 (*7, 32, 42*).

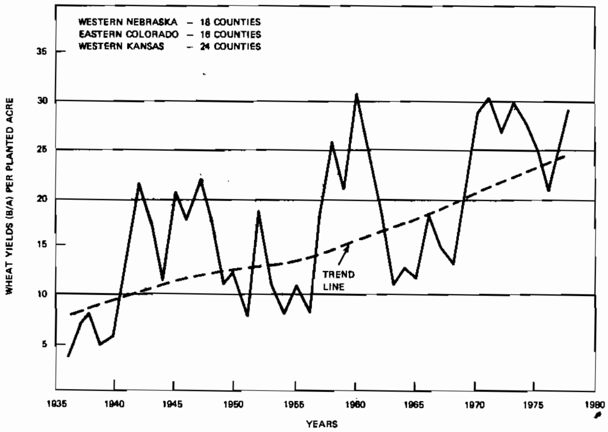

FIGURE 10.—Winter wheat yields, summer fallow area, central Great Plains, 1936-77 (*7, 32, 42*).

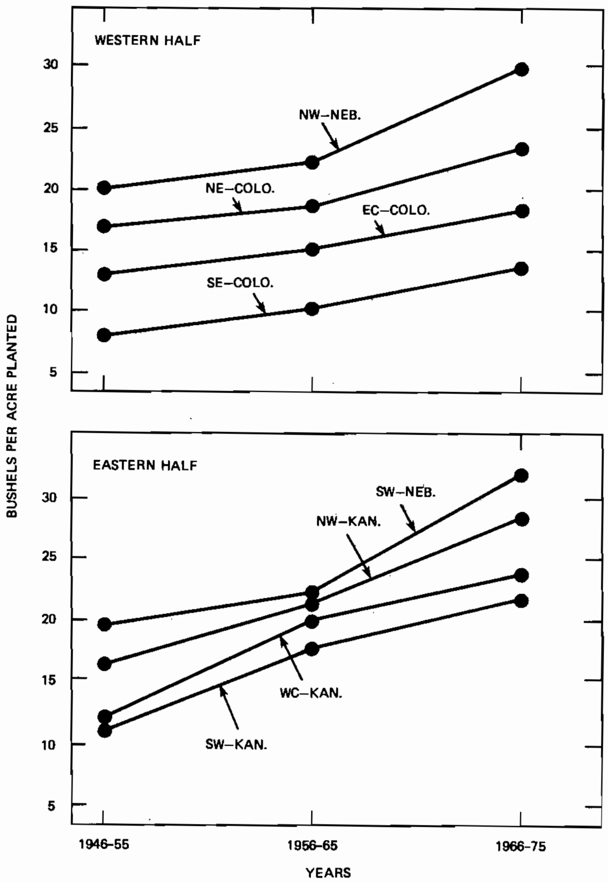

FIGURE 11.—Increase in winter wheat yields grown on summer fallow, central Great Plains, 1946-75 (*7, 32, 42*).

TABLE 11.—*Historical increase in winter wheat yields in the summer fallow area, central Great Plains, by climatic districts* (7, 12, 32, 42, 57)

Climatic districts	Major counties	Average annual precipitation	Mean temperature	Average acres planted	Winter wheat yields 1946-55	1956-65	1966-75	Gain yield[1]	30-year average
Western half	*Number*	*Inches*	*°F*	*Thousands*	*Bu/acre planted*				
Northwest Nebraska	9	17.5	48.5	875	19.8	21.7	29.4	9.6	23.5
Northeast Colorado	6	17.0	49.3	803	16.4	18.1	23.2	6.8	19.1
East-central Colorado	6	15.8	49.6	1,001	12.6	14.7	18.1	5.5	15.1
Southeast Colorado	4	15.4	53.0	795	7.4	9.9	13.3	5.9	9.9
Total or average	25	16.4	50.1	3,465	13.9	16.2	21.1	7.2	17.0
Eastern half									
Southwest Nebraska	9	19.6	52.9	721	19.0	21.8	31.8	12.8	23.9
Northwest Kansas	6	19.2	53.5	989	16.0	21.0	28.2	12.2	21.3
West-central Kansas	8	19.5	55.0	1,161	12.3	19.8	24.1	11.8	18.4
Southwest Kansas	10	18.9	56.3	1,399	10.7	17.6	21.3	10.6	16.0
Total or average	33	19.3	54.4	4,270	13.7	19.7	25.4	11.7	19.2
Average all districts	58	17.9	52.3	7,498	13.8	18.1	23.5	9.8	18.1

[1]Gain yield 1966-75 compared with 1946-55.

TABLE 12.—*Summary of planted wheat acres abandoned in the summer fallow area, central Great Plains, by climatic districts* (7, 32, 42)

Climatic districts[1]	Major counties	Percentage of acres abandoned 1946-55	1956-65	1966-75	30-year average
	Number	*Percent*			
Western half					
Northwest Nebraska	9	13	12	6	10
Northeast Colorado	6	16	16	13	15
East-central Colorado	6	22	25	19	22
Southeast Colorado	4	45	47	34	42
Average	---	24	25	18	22
Eastern half					
Southwest Nebraska	9	10	9	6	8
Northwest Kansas	6	17	13	8	13
West-central Kansas	8	23	17	15	18
Southwest	10	26	19	18	21
Average	---	19	15	12	15

[1]See table 11 for precipitation and temperature data.

production approximates 96 percent from wheat-fallow rotations and only 4 percent continuously cropped wheat (*27*).

The acreage planted annually to wheat averaged 7.5 million from 1946 to 1977. Acreage data on figure 9 indicate the forces that can cause these plantings to fluctuate from year-to-year. With the exception of the 1957 Soil Bank year, annual plantings exceeded 6.5 million in all years from 1944 to the present time. Over 9 million acres were planted from 1947 to 1953 in response to wartime and postwar demands. There has been a gradual leveling off to about 6.5 to 8.0 million acres since 1953 because of land adjustments to allotment restrictions and increasing conversion of wheatland to ground water irrigation development.

Wheat yields are reported here on a planted acre basis as reflecting the risk factor rather than on a harvested acre basis. High losses of wheat acres planted are not unusual in some areas and years. Yields for the entire region as graphed in figure 10 are revealing from three standpoints:

- Yields varied widely from year to year in normal response to climatic conditions; however, the general trend is consistently upward from 1941 to 1977 at the rate of 0.4 bu/acr/year.

- Three distinct down yield cycles and three up or high yield cycles of varying duration occurred. Each successive down cycle showed yield improvement over the previous down cycle. Each successive high yield cycle showed improvement over the previous high cycle.
- Despite periodic drought conditions from 1969 to 1977, there is no yield trend downward, and present conditions appear favorable for the 1978 crop.

Yield averages (planted acre basis) for these cycles are as follows:

Years	Down cycle	Up cycle
	Bu/acre	
1931[1]-40	6.8	---
1941-48	---	14.2
1949-56	11.1	---
1957-62	---	22.9
1963-68	13.9	---
1969-77	---	26.8

[1]Actual beginning of 1930's general drought, becoming very intense by 1934.

I used 1946 as a base point year for further analysis of wheat yields county-by-county and then grouped counties into eight subdivisions based on climatic differences and geographic location. By 1946, summer fallow had been universally adopted for winter wheat production throughout the west-central Great Plains, and the final plowout of native grass was well along.

Data pertaining to the yield of wheat from these subdivisions by 10-year averages for 1946-55, 1956-65, and 1966-75 are given in table 11 and figure 11. Yields were increased in each subdivision for each of the 10-year intervals but at different rates. For all subdistricts combined, yields averaged 13.8, 18.1, and 23.5 bu/acre/year for periods 1946-55, 1956-65, and 1966-75, respectively. The average yield increase of the latter two periods compared with 1946-55 was 0.43 and 0.54 bu/acre/year in that order. Additional yield trends are listed below:

- All 58 counties showed a progressive increase in wheat yields per planted acre.
- Long term yield differences persisted between climatic districts even though yields improved in all districts.
- Yield increases were greater in the northern half of the climatic districts than in the southern half by a margin of 10.35 to 8.45 bu/acre.
- Yield increases were greater in the eastern half of the districts than in the western half by a margin of 11.7 to 7.2 bu/acre.
- The greatest yield increase differential occurred between the northeast quarter (southwest Nebraska and northwest Kansas) and the southwest quarter (east-central Colorado and southeast Colorado) at 12.5 to 5.7 bu/acre.

These trends show that the greatest yield increases occurred with greater average precipitation and cooler temperatures. This is dramatized even more by individual county performance. Red Willow, Frontier, Hitchcock, and Hayes Counties in southwestern Nebraska showed yield increases of 16.6, 16.3, 15.8, and 15.7 bu/acre, respectively, compared with yield increases of only 3.3, 3.5, and 3.4 bu/acre for the southern, drier, and warmer Morton and Stanton Counties, Kans., and Baca County, Colo., in that order.

For the entire 30-year average, wheat yields varied about 2.0 bu/acre per inch change in annual precipitation and 2.0 bu/acre per 1 °F change in annual temperature. Thus, a given climatic district "A" averaging 2 inches less rainfall and 2° warmer than a given district "B" results in a 8 to 9 bu/acre lower average long term yield.

Wheat acres are often abandoned because of disasters such as hail, disease, poor seedbed preparation, and especially soil water shortages induced by low-quality summer fallow in combination with periodic droughts. Data on table 12 show a decline in wheat acres abandoned for all eight climatic districts as a function of time and technology. For example, acres abandoned in western Nebraska averaged 11.5 percent during the 1946-55 period and declined to only 6.0 percent in 1966-75. Likewise in western Kansas, acres abandoned declined from 22 percent in 1946-55 to 14 percent in 1966-75; and eastern Colorado from 28 percent to 22 percent for the same time interval. The risk factor involved with a marginal climate is dramatized by the abandoned acreage in southeastern Colorado, which averaged 42 percent over a 30-year period, which was about double any other climatic district and four and one-half times greater than western Nebraska.

There was no evidence that changes in weather patterns can be credited with any increase in yields. In fact, weather data from Akron and Burlington, Colo., North Platte, Nebr., and Colby, Kans., indicate a decrease in favorable weather from 1950 to 1975 compared with 1916 to 1950.

The yield increases must be credited to the periodic adaptation of improved technology. From consultation with a number of plant breeders, agronomists, soil scientists, and engineers, credit for type of technology is estimated as given below:

	Percent
• Improved stored soil water in fallow Better mechanical and herbicide weed control Better use of stubble-mulch More runoff water engineering	45
• Improved wheat varieties Shorter straw Improved tillering capacity Earlier ripening to escape heat damage Disease resistance	30
• Improved planting equipment Deep furrow drill to reach seedbed water More acres per day	8
• Improved harvesting equipment Faster, cleaner	12
• More fertilizers on sandy and weak soils	5

With continued improvement of water intake and water use efficiency, there is little reason for wheat yields to level off now or in the foreseeable future. There seems to be sufficient resources, despite periodic droughts, that the entire area could average 30 to 32 bu/acre by 1990 or earlier, assuming a continued 0.4 bu/acre/year increase as has occurred the previous 40 years.

VI. STRATEGIES ON THE DRAWING BOARD

Source Value of Water

Data for crops are often plotted with yield on the Y-axis and total water use on the X-axis. Total water use usually implies soil water consumption plus crop season rainfall. Some investigators also use the term (ET), referring to water use by evaporation (E) plus plant transpiration (T). In either case, water sources are not divided into logical components of yield value. How valuable is an inch of water already stored in the soil compared to an inch of rain? How valuable is rainwater in relation to various stages of plant growth or cold season rain versus warm season rain? Investigators do not know, but some estimates are being made.

Estimates of source value of water in terms of water use efficiency from past and present research plots at Akron are given in table 13. The data clearly demonstrate that the source value of water is highly related to evaporation exposure. Thus, stored soil water at seeding time involving very little evaporation is shown to be several times more efficient than crop season rainfall and roughly 1.7 times more efficient than captured snowmelt, captured runoff water, or sprinkler irrigation. An arbitrary index of efficiency is listed below for the averages given in table 13.

Source water for plants	*Water use efficiency index*
Stored soil water	100
Captured snowmelt in soil	89
Sprinkler irrigation plus evaporation	62
Captured runoff water plus evaporation	57
Captured snowmelt plus evaporation	57
Cool season rainfall plus evaporation	25
Warm season rainfall plus evaporation	22

Obviously, the listing on table 13 does not include a uniform group of crops for each value; nevertheless, the estimates show similarities within groups and probably reflect, in a general way, what is going on in the field.

We should not expect water-use efficiency to be a constant value for a given source of water throughout the growing season for any commercial crop. As shown in figure 12, the water-use efficiency for winter wheat increased from early in the spring to higher values at the soft dough stage of grain development. These values range from 400 lb/acre-in on April 18 to about 1,400 lb/acre-in June 6 to 13. This variation should be expected because the plant is extending a vigorous root system in relation to top growth early in the spring, whereas the extension of roots is largely completed after heading and, therefore, a greater percentage of water is converted into top growth dry matter units. The data for figure 12 included 80-percent consumption from stored soil water and 20-percent crop season rainfall from April 4 to July 3.

TABLE 13.—*Estimated source values of water for various crops, U.S. Central Great Plains Research Station*

Data years	Field trials	Water source	Type crop	Water use efficiency
No.	*No.*	*Type*		*Lb/ acre-in*
21	5	Soil water at seeding[1]	Winter wheat	845
4	1	--------do--------	Winter rye	1,200
9	2	--------do--------	Proso millet	1,000
4	1	--------do--------	Hay millet	780
4	1	--------do--------	Sudangrass	600
5	1	--------do--------	Grain sorghum	715
Crop avg.				855
4	1	Crop season rainfall,[1]	Winter rye	210
4	1	cool season	Winter wheat	220
4	1	Crop season rainfall,[1]	Hay millet	210
4	1	warm season	Sudangrass	160
Crop avg.				200
4	1	Captured snowmelt evaporation[1]	Winter rye	500
4	1	--------do--------	Winter wheat	530
4	1	--------do--------	Hay millet	450
4	1	--------do--------	Sudangrass	490
Crop avg.				480
4	1	Captured snowmelt, to soil[1]	Winter rye	770
4	1	--------do--------	Winter wheat	810
4	1	--------do--------	Hay millet	700
4	1	--------do--------	Sudangrass	780
Crop avg.				765
7	3	Captured runoff water[2]	Corn	[3]420
6	1	--------do--------	Millet	640
9	2	--------do--------	Sorghum	455
5	1	--------do--------	Winter wheat	455
Crop avg.				490
	1	Sprinkler irrigation[4]	Corn	605
	1	--------do--------	Grain sorghum	455
Crop avg.				530

[1]B. W. Greb, unpublished data, 1962-77.
[2]R. H. Mickelson, unpublished data, 1964-76.
[3]Some water loss by deep percolation on corn.
[4]R. W. Shawcroft, unpublished data, 1977.

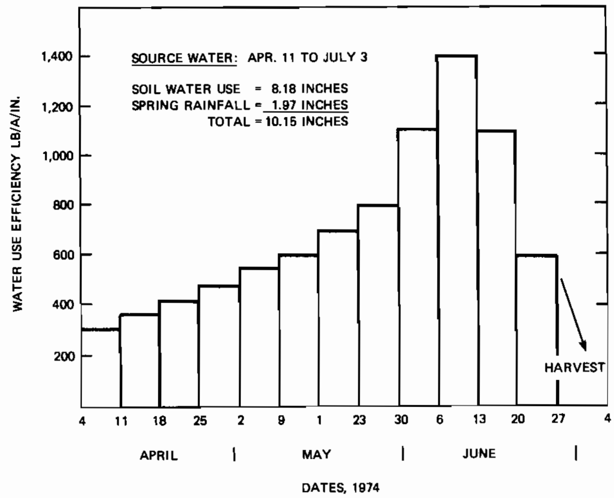

FIGURE 12.—Water use efficiency for winter wheat (Scout 66) in spring of 1974 under optimum soil water conditions. Data extrapolated from samplings taken every 20 days at the U.S. Central Great Plains Research Station.

Similarly, the value of crop season rainfall should vary widely in relation to stages of plant growth, size of rainfall per event, and frequency of rainfall events. Light showers of less than 0.2 inch are generally of little value unless succeeded by daily showers of equal quantities during cool-humid conditions. Rains of less than 0.5 inch during the heat of summer are also of limited value. Yet crops such as winter wheat and proso millet will respond very favorably to 1.3 to 2.0 inches of rain during the flowering stage when both peak water demand and water use efficiencies are high.

The objective of this particular discussion section is to point out these various source values of water, and perhaps show where the greatest conservation efforts should be applied in the future. In discussions on summer fallow and for preplant irrigation, the emphasis is on increasing stored soil water at seeding time. The data given here lend support to this idea.

Evaporation Suppression

Evaporation remains the greatest cause of water loss in the Great Plains and the hardest to conquer. Economic systems, other than mulches for evaporation suppression, have not proved successful. Some attempts have been made to spray chemicals, such as monomolecular films of hexadeconal, on bodies of open water to suppress evaporation. Biochemical decomposition, windy surfaces, or reactions with chemicals in the water have tended to destroy these films. Another possible way of reducing evaporation includes spraying flat soil surfaces or hardening soil clods (gravel mulch principle) with plastic films.

There are probably many long-chain organic chemicals that will be tested in future field evaporation experiments in the field. Any chemical would have to meet the following criteria: (1) Low in cost and easily applied, (2) compatible with the air-soil-plant environment, and (3) effectively long lived to prove positive in a water-balance system.

Reductions of Energy Use

Shifting systems of farming usually imply a shift in energy input in terms of fuel, fertilizers, pumping costs, grain drying, and product handling in relation to the kilocalorie energy value of the crop. These shifts are evolving whether crop production is threatened by drought or under normal rainfall conditions. Since 1970, it has been suggested that energy consumption could be reduced by using lower rates of nitrogen fertilizer on corn and more solar energy for drying grain and by better metering of irrigation water in relation to crop demands.

Minimum tillage and no-till farming are potential energy savers on Midwest corn and, to some extent, on western wheatfields. Present estimates on wheat fallow with minimum tillage utilizing preemergence herbicides indicate that the energy input would be reduced 15 to 20 percent, at the same time increasing yields by 15 to 20 percent. A modern spray rig can cover 50 acres much quicker and with less power than some of our new super-sized tractors. Costs are rising so fast that unnecessary tillage in tomorrow's world will be a luxury few can afford.

Yield Predictions by Remote Sensing

We refer here to color images being recorded by remote sensing satellites revolving around the earth in high-altitude flight paths. Remote sensing is playing an ever-increasing role in weather forecasting, hydrologic estimates of snowmelt runoff from complex mountain ranges, and numerous micrometeorological measurements at specific experimental soil-water-plant systems. The hardware is expensive, but the cost is amortized by reducing manpower required to operate onsite instruments.

Advances in high-speed, high-resolution photography is largely beyond the average layman's knowledge or awareness. Such photography may now make it possible to predict crop yields from great distances. It is already being used to detect crop, orchard, and forest diseases and pest invasions.

The success of crop yield predictions will depend upon obtaining a high correlation between color images and ground truth performance of a growing crop. For winter wheat, such measurements might include soil water at seeding time, soil fertility, quality of stand, soil temperatures, net radiation, leaf area index, and other items. The health of the crop is then reflected in growth patterns, which are photographed as the season progresses. This type of research is just now being initiated with no preliminary results to indicate probable success.

Should this concept prove successful, it should be possible to maintain a continuous inventory of the world's major food and animal feed commodities in the field such as rice, corn, wheat, and grain sorghums. Projections of increasing or decreasing supplies of any of these commodities would then influence world trade.

Regardless of the success or failure of remote sensing for crop yield prediction, present measurements of wheat field conditions, including intensive instrumentation of wheatfields, should produce valuable information on the cause and effect of plant growth. These data would then provide new insights on how to maximize yields with less input.

Blind Alleys?

Drought Resistant Plants

Because drought is a constant threat to western agriculture, proposals have been made to increase the drought resistant capability of common domestic plants such as wheat, barley, sorghum, and corn by intensified plant breeding programs. Increasing drought resistance may be much more difficult than many people realize. What is meant by drought resistance? H. L.

Shantz (*45*) listed four types of plant adaptation to drought situations as follows:

Drought escaping.—Short season, short height annual grasses, flowers, and herbs that respond to a brief water supply, and thus complete their life cycle quickly. Seeds may be dormant for years before responding to another rain.

Drought evading.—High water use efficiency, fast-growing roots, short season, and a high ratio of seed to straw. Various millets are in this category.

Drought resistant.—Long-lived succulent cacti that impound water in their tissues; leaves are narrow spines or needle form. Needs a large surface area per plant, thus low population density.

Drought enduring.—Some annuals but especially perennial grasses, such as buffalo and blue grama, which go into temporary dormancy under water stress and can resume growth as water and favorable temperatures are again available.

Using the above terminology, drought resistance is hardly what the plant breeder will be looking for. Perhaps drought evading or drought enduring more nearly fits commercial crop possibilities.

Others, besides myself, have observed plants under water stress for many years in the Great Plains environment and have noticed certain patterns of response. When plants such as wheat, millet, and sorghum are stressed anytime during elongation, the growth tip cells are damaged so that no amount of supplemental water will restore full yield potential. At this stage, rainfall usually comes too little and too late to be of much value. Delayed growth because of stress sometimes delays plant maturity until too late in the season with the result that the grain suffers frost damage as is the case for corn and sorghum in cooler temperature climates. For wheat, severe water stress at early heading followed by plentiful water usually produces undesirable sucker tillers and heads that remain green while the remainder of the plant is mature. This wastes water and makes harvest very difficult. Many older wheat, corn, and sorghum varieties were slightly more tolerant of water stress than some new varieties; however, these older varieties also had a lower yield capacity and could not perform when modern conservation practices increased water supply.

Perhaps breeders will be able to genetically derive new wheats that will be able to extract more water from the soil and thus lower the effective wilting point. Reducing the wilting point from 8 to 7 percent on a silt loam soil would supply an additional 0.16 inch of water per foot from 5 ft of soil. This would increase the yield by 3 to 4 bu/acre. Nevertheless, this new one-percent soil water deficit would have to be made up the succeeding fallow season.

Another possibility for enhancing drought endurance is to reduce leaf size or leaf numbers without reducing photosynthetic capacity. This implies lower transpiration per unit of water for cell reproduction. Dwarfing of plants has not always worked out in terms of drought tolerance. In hybrid sorghums, for example, the leaves were compressed on shorter stalks, but the number of leaves remained the same and, in some cases, very large leaves resulted. Breeding shorter stalks for sorghum, however, produced other beneficial effects such as uniform height, ease of harvest, uniform maturity, and high yield capacity.

We discussed genetic engineering in section III and also here. Hopefully, future proposals will be based on a greater understanding of supply and demand of available water.

Mulches and Pathogens

For many years, straw-stalk mulches were considered by some microbiologists, pathologists, and entomologists as potential sources of plague and pestilence. In some laboratory results, as obtained in warm wet environments, data confirmed the possibility that decomposing vegetable matter produced short-life toxins and harbored media for disease spores and insects.

For much of the Great Plains, however, three factors tend to minimize aerobic and anerobic pathogens. First, the volume of mulches produced by normal farming is quite low, seldom averaging over 2 tons/acre for wheat straw. Second, low humidity, low rainfall, and high wind velocities tend to keep mulches dry for much of the season. Last, when short, warm, wet conditions do occur, decomposition is very rapid because straw strength is greatly weakened over winter and soils in contact with straw are fertile, thus favoring accelerated bacterial activity. By the time wheat is planted, the odds greatly favor minimum carryover of any toxic effects.

In 25 years of fieldwork, I have not yet witnessed a negative toxic, disease, or an insect invasion due to crop mulches in dryland. Those who propose breeding new plants to be more tolerant of the new diseases produced by mulches may not be investing their efforts in the most profitable direction. More evidence should be gathered to see if such damage really exists. Potential outbreaks would most like occur with heavy mulches under no-till systems in the Midwest and parts of the Southeastern United States if at all. The basic problem in the Great Plains is that of too little mulch.

Weather Modification

Modifying weather involves the seeding of clouds with nuclei materials, usually silver iodide or carbon dioxide. The whole concept seems simple and with enormous possible benefits. Unfortunately, during drought periods, clouds are absent or thin.

The recent and present activity is divided into three fields of interest: (1) Cloud seeding warm-season convection storms for hail suppression, (2) seeding cool-season storm fronts to increase rainfall, and (3) seeding snowstorm fronts in high mountain areas. The greatest success to date has been in seeding snow clouds where a 12- to 18-percent increase in snowfall was reported by L. O. Grant (personal commun.). Snowstorms are divided into three categories based on ambient temperature and snowload. About one-third of these fronts will produce 40 to 50 percent more snow upon seeding, whereas the remaining 67 percent of storm fronts will respond with no change or will actually produce less snow. The key to success is in identifying the favorable criteria.

Predicting the effect of seeding warm-season convection storms or broad spring-season storms fronts is confounded because of the complexity of cloud physics and the extreme high-energy systems involved. Secondly, whether seeding these storm systems modifies clouds or not, the implication opens a host of legal, social, political, ethical, and engineering problems.

VII. DISCUSSION AND CONCLUSIONS

Drought is a normal part of our climatic environment and not unusual. Too often our society has overreacted to drought as a negative "Act of God" and did not make proper adjustments in population density, water use, farming, forest utilization, or placement of industrial sites. As our knowledge expands our actions should be wiser.

Rain dances are a quaint plea for rain, and cloud seeding is an ill-perfected technique. We remain with the reality of handling water that arrives either by natural precipitation or as a result of being pumped from underground aquifers. Our premise for dealing with drought included two broad avenues: (1) *maximizing soil water intake,* which is like increasing deposits to a bank account; and (2) *maximizing water use efficiency,* which is analogous to upgrading low rates of simple interest to higher rates of compound interest. With these concepts in combination, crop yields can be significantly increased with no greater volume of water and sometimes less, regardless of source.

In the Great Plains, both on dryland and irrigated land, the time has arrived when land operators should become more and more familiar with the simple techniques involved with probing soil profiles for water content during the dormant season, at seeding time, and at critical stages of crop growth. In this manner, yield projections can be estimated and management decisions adjusted to the true water situation. For example, the hydraulic soil sampler costs much less than the new tractor, and can be much more valuable when properly used.

We have already made good progress in water management as shown in figure 13. These curves and time dates symbolize the historical yield increases well known for corn, grain sorghum, wheat, soybeans, and other crops such as cotton, legumes, and barley as a function of time and technological breakthroughs.

In a speech a few years ago, T. J. Army[3] outlined date from Witwer (*61*), showing average

[3]T. J. Army. Higher plateaus of productivity. Annual meeting of the American Society of Agricultural Engineers. Davis, Calif., June 23, 1975. Unpublished.

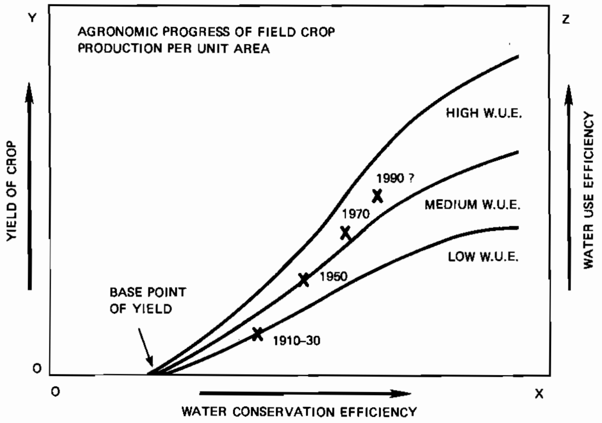

FIGURE 13.—Hypothetical U.S. crop yield projection.

yields of major commodities in 1974 as compared with record yields (table 14). The average yields reflect a temporary plateau involving constraints of weather, management practices, weed and disease control, and a host of other inputs that go into producing crops over a broad spectrum of land types, climate, elevation, and latitude. The record yields, on the other hand, reflect actual biological potential in which all constraints were removed. T. J. Army concluded as follows, "To break both or either of these statistical yield plateaus is certainly within the realm of modern science and technology. But the raising of each yield plateau will require different technological and educational approaches. The doubling of average yields is technically feasible and will be easier to accomplish than the doubling of record yields."

TABLE 14.—*Average and record yields of major U.S. crops* (61)

Food crop	Average yield 1974	Record yield	Ratio of record yield to average yield
	Bu/acre	*Bu/acre*	
Corn	72	307	4.3
Wheat	28	216	7.7
Soybeans	24	110	4.6
Sorghum	45	320	7.1
Oats	48	296	6.2
Barley	38	212	5.6
Potatoes	420	1,400	3.2

In conclusion, the immediate components that need continuous attention for tomorrow's agriculture are only refinements of where we have already been.

- We will need much improved water management under all agricultural systems be it level land or hillsides, humid, subhumid, semiarid, arid, or irrigated.
- We will need research breakthroughs to increase the photosynthetic capacity of our present crops and to develop new or improved crops by genetic manipulation.

Other factors of crop production, especially weed control, fertility monitoring, and energy consumption, will need to keep pace with the demands. The future of agriculture, regardless of drought, is optimistic, and past performance verifies this optimism.

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IX. SCIENTIFIC NAMES OF COMMON CROPS AND GRASSES MENTIONED IN THIS PUBLICATION

Common Name	*Scientific Name*
Barley	***Hordeum vulgare*** **L.**
Corn	***Zea mays*** **L.**
Millet, hay types	***Setaria italica*** **L.**
Millet, proso types	***Panicum miliaceum*** **L.**
Oats	***Avena byzantina*** **K. Koch**
Rye	***Secale cereale*** **L.**
Sorghum	***Sorghum bicolor*** **(L.) Moench**
Sudangrass	***Sorghum sudanese*** **(Piper) Stapf.**
Wheat, spring	***Triticum vulgare*** **Vill.**
Wheat, winter	***Triticum aestivum*** **L.**
Blue gramagrass	***Bouteloua gracilis*** **(H.B.K.) Griffiths**
Buffalograss	***Buchloe dactyloides*** **(Nutt.) Engelm.**
Crested wheatgrass	***Agropyron cristatum*** **(L.) Gaertn.**
Intermediate wheatgrass	***Agropyron intermedium*** **(Host) Beauv. var. *intermedium***
Russian wildrye grass	***Psathyrostachys juncea*** **(Fisch.) Nevski**
Tall wheatgrass	***Agropyron elongatum*** **(Host) Beauv.**

U. S. GOVERNMENT PRINTING OFFICE : 1979 O - 295-072