MANAGING DEFICIT WATER SUPPLIES[1]

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ABSTRACT

Deficit irrigation involves using a limited water supply over a larger area than can be adequately irrigated for high yields. It is widely practiced for irrigation of drought resistant crops in the Southern High Plains. Management practices for successful deficit irrigation have been studied at Bushland, Texas, since the early 1960's. Research results and experiences of the author and colleagues are summarized as 7 RULES for deficit irrigation management. These are presented and discussed as follows: RULE 1 - Only consider deficit irrigating soils that are relatively deep and have moderate to high water storage capacity; RULE 2 - Consider deficit irrigation for the drought resistant crops; RULE 3 - Consider increasing the contribution of precipitation to crop water needs; RULE 4 - Consider crop growth stage and cutoff date in managing water; RULE 5 - Consider the need for preplant irrigation; RULE 6 - In furrow systems, consider management for reducing water applied by reducing water intake and field runoff; and RULE 7 - Consider modifying some cultural practices for deficit irrigation.

INTRODUCTION

I appreciate the opportunity to meet with you and discuss my experiences with deficit irrigation. My first professional talk as an agricultural engineer working in irrigation research at Garden City, Kansas, was to a similar meeting (Tri-State Irrigation Clinic) at Goodland, Kansas, in 1959. At that meeting, I discussed "Irrigating grain sorghum" and included managing limited water supplies. Thus, this subject has been one that I have had an interest in for the past 30 years.

During the major irrigation expansion in the Texas High Plains (the mid 1940's through the 1950's, Fig. 1) very little concern surfaced about groundwater depletion. The management practices developed emphasized adequate irrigation and high yields. However, concern developed in the 1960's about water table and well yield decline and ambitious ideas were promoted for water importation and artificial groundwater recharge. In 1962, I transferred to the ARS Field Station at Bushland, Texas, and initiated a project on management of limited

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irrigation. Research on various aspects of limited irrigation has continued and results and personal experiences are discussed in this paper as deficit irrigation. Major irrigation adjustments have occurred in the Texas High Plains since about the mid 1970's that resulted in reduced groundwater pumped for irrigation from 8.1 million ac.-ft. in 1974 to 5.0 million ac.-ft. in 1984 (Musick et al., 1988). This reduction in groundwater pumped resulted from both the reduction in irrigated area (Fig. 1) and increased use of deficit irrigation for wheat sorghum and cotton.

Deficit irrigation involves using a limited water supply over a larger area than can be adequately irrigated for high yields. The reduced per acre water application increases the risk of significant yield reduction. While modest yield reductions are allowable in order to use available limited water supplies to substantially increase the irrigated area, deficit irrigation management should be carefully considered before it is practiced. For this presentation, I have summarized important considerations that I believe are involved in the successful practice of deficit irrigation. These are presented in the following sections as rules to consider.

7 RULES FOR MANAGING DEFICIT IRRIGATION

RULE 1. Only consider deficit irrigation on soils that are relatively deep and have moderate to high profile water storage capacity.

As seasonal water application is reduced, the use of moderate to high water storage soils and early season profile wetting before the major water use growth period begins is important. Moderate to high water storage soils provides root zone water reserves that allow water deficits to develop gradually which improves the conditioning of plants to stress. Soils that have shallow rooting depths or course-textured profiles that have low water storage capacities probably should not be deficit irrigated. These soils allow rapid development of stress to more severe levels and increase the risks of excessive yield reductions.

The moderate to high water storage soils mostly have profile depths of about 4 to 8 ft. and plant available water storage capacities of about 12 to 15% by volume or total profile available water contents of about 6 to 12 in. Some soils with sandy surface textures have fine-textured subsoils and relatively high profile water storage capacities and can be successfully managed under deficit irrigation. This is the case for the fine sandy loams in the Southern High Plains that are successfully managed for deficit irrigation of cotton.

Studies with grain sorghum at Bushland, Texas, on Pullman clay loam (about 4 ft. profile depth to cliche) and on Richfield clay loam at Garden City, Kansas, (about 7 ft. rooting depth on a deep silt loess profile) indicated that about twice the total soil water depletion could be allowed on the Richfield before yield reduction occurred (Musick and Sletten, 1966). Seasonal water use was similar at the two locations and the Pullman site required one additional 4 in. seasonal irrigation to produce similar yields, Fig. 1. Clearly the Richfield site would be the best soil for successful management of deficit irrigation.

RULE 2. Consider deficit irrigation for the drought resistant crops.

The major crops that are grown under deficit irrigation in the Central and Southern Great Plains are the same crops that are grown under dryland conditions. These are wheat and sorghum in the Central Plains and wheat, sorghum, and cotton in the Southern Plains. Minor crops are millet, barley, forage sorghums, cool season grasses, seed alfalfa, sugarbeets, sunflowers, and grapevines (Musick and Walker, 1987). Because of yield sensitivity to water deficits, corn should only be grown under adequate irrigation for high yields (Musick and Dusek, 1980a).

Drought resistance consists of (1) the ability of plants to tolerate plant water deficits while continuing to grow, and (2) the ability to avoid and thus delay plant water stress through deep rooting and greater use of lower profile water storage. Crops can possess both tolerance and avoidance mechanisms. Tolerance is the primary drought resistance mechanism of wheat and sorghum, both tolerance and avoidance through deep rooting are important for sugarbeets and avoidance is the primary mechanism for deep-rooted sunflowers.

Deficit irrigated crops are mostly grown on soils that permit moderate to deep rooting to about 4 to 8 ft. In the absence of profile restricting zones, deep rooting crops such as sunflowers, sugarbeets, and seed alfalfa extend roots for water extraction to the 7 to 8 ft. depth and wheat, sorghum, and cotton, mostly to the 4 to 6 ft. depth. Sparse rooting density in about the lower one-fourth of the profile limits plant ability to fully extract all the profile available soil water.

Osmotic adjustment (the active accumulation of solutes during developing water deficits in cells of leaves, roots, and meristematic tissue) is believed to be an important aspect of drought resistance of wheat and sorghum that favorably influences physiological processes (Turner, 1986). It allows plants to delay stomata closure, delay visual evidence of stress such as leaf roll, and helps maintain cell pressures for continued expansion of leaves and extension of roots. Thus, it permits plants to delay and moderate the stress effects on yields that can occur under deficit irrigation. Drought resistance permits plants to maintain improved physiological processes for resuming normal recovery growth following stress termination by irrigation.

RULE 3. Consider increasing the contribution of precipitation to crop water needs.

Precipitation increases in importance for meeting crop water needs in areas where deficit irrigation is practiced (Stewart and Musick, 1987). In the irrigated semi-arid Central and Southern Plains, precipitation normally provides about 30 to 60% of seasonal crop water needs of crops grown under deficit irrigation. Deficit irrigation management increases yield risks compared with adequate irrigation and normal to above normal precipitation is usually relied on to meet expected yield goals. In the major dry seasons, increased water application is needed both to compensate for reduced precipitation and for the increased evaporative demand for water use associated with prevailing warm, dry air.

The contribution of precipitation in meeting crop water needs and thus reducing irrigation requirements can be enhanced by (1) using precipitation for stand establishment without preplant irrigation, (2) partial wetting of the profile during irrigation which allows some storage capacity for precipitation (reducing application by use of wide-spaced furrows, irrigation of wheel track furrows, or use of surge-flow to reduce water intake), (3) reducing or eliminating precipitation runoff (use of conservations tillage, furrow dams, and land leveling), (4) reducing application during above normal precipitation periods, and (5) managing irrigation for early cutoff to more fully utilize available profile water storage by the end of the season.

Early irrigation cutoff increases storage capacity for nongrowing season precipitation between harvest and planting the next crop and thus the efficiency of storage. In a 3-yr. test involving grain sorghum irrigation treatments at Bushland on Pullman clay loam, precipitation storage efficiency after harvest ranged from the 40 to 50% range when the soil profile was dry after harvest from early irrigation cutoff at boot stage to about 10% or less when the profile was wet after harvest from late cutoff at dough stage, illustrated in Fig. 3, (Musick, 1970).

During major drought seasons, the lack of precipitation may necessitate shifting limited water supplies to more stress sensitive crops such as corn or soybeans and crop area under deficit irrigation may need to be reduced. Adjustments were observed in the Southern High Plains during the 1980 drought season as some water supplies were shifted from sorghum to corn and some normally irrigated sorghum fields were managed as preplant irrigation only.

RULE 4. Consider crop growth stage and cutoff date in managing water application.

Stages of crop growth when deficits are allowed and irrigations are applied can have a substantial effect on yield response to irrigation. Yield response by sorghum to applied irrigation is normally appreciably lower during early season vegetative growth, increases substantially during boot stage through flowering and declines to a lower response level during grain filling (Musick and Dusek, 1971). This effect is illustrated in Table 1 for test data from Etter, Texas, on Sherm clay loam (Shipley and Regier, 1975). Timing of water deficits involving development stages can result in a considerable range in sorghum yields for a given level of seasonal water use, illustrated in Fig. 4 from the data by Musick and Dusek (1971).

The timing of irrigation in relation to critical development stages increases in importance as the number of seasonal irrigations are reduced and plants experience increasing levels of plant water stress, illustrated in Table 2. One seasonal irrigation for sorghum in the Texas High Plains should not be applied as the only irrigation either early during vegetative growth or late during grain filling. However, at higher water levels involving additional applications for high yields, the yield contribution of both early and late irrigation increases. The high yield response to irrigating grain sorghum during boot stage through flowering, illustrated in Tables 1 and 2, is associated with preventing critical stage water stress from reducing seed numbers per head and number per unit ground area. Stress effects on reducing seed numbers is a more sensitive process affecting yields than effects on reducing seed weight.

When the growth stage response to deficit irrigation of wheat from studies at Bushland is compared with sorghum, irrigation during early spring vegetative growth is more critical for wheat. This comparative growth period occurs about six months after planting winter wheat compared with one month after planting sorghum. Soil water depletion is normally greater for wheat than for sorghum at the comparative stage because of the relatively dry winters and water use from fall to early spring. Although wheat is more responsive to irrigation during early vegetative growth, it is less responsive to irrigation during grain filling because of much higher precipitation. Normal mid-May to mid-June precipitation during grain filling of wheat is almost double mid-August to mid-September grain filling precipitation for sorghum. In 3 to 6 years of tests with wheat at Bushland, precipitation following an early grain filling irrigation prevented any yield response to the irrigation (Musick and Dusek, 1980b; Musick et al., 1984; unpublished).

Tests have shown that wheat has greater stress tolerance during grain filling than sorghum with leaf death occurring following water potential decline to about -30 to -32 bars for sorghum (Eck and Musick, 1979) and to greater than -40 bars for wheat (Musick and Porter, 1989). The moderate yield reduction from stress during grain filling of wheat is associated with increased translocation to the grain of soluble carbohydrates stored in the stems. (Leaves that senesce during grain filling also translocate some assimilates to the grain). In 1988 tests at Bushland, translocation during grain filling of dry matter accumulated by flowering was associated with 49% of the grain yield when late boot stage irrigation cutoff resulted in grain filling stress that reduced yield by 9%. The preflowering contribution of dry matter to grain filling under adequate irrigation was 19%. Thus, under moderate grain filling stress that accelerated the loss of green leaf area and probable decline in photosynthesis (not measured), 30% of the grain weight was associated with increased translocation of previously stored dry matter.

Although afternoon stress may be allowed under deficit irrigation of crops possessing drought resistance, it is important that the stress be terminated by irrigation before it increases in severity to the extent of preventing overnight recovery. Stress that develops to this severity greatly slows growth and can cause rapid loss of yield potential.

In summary, by starting the season with a wet soil profile, good management of deficit irrigation can involve a delayed startup, depletion of profile soil water storage to about 30% available before irrigation compared with the more conventional 50% available used for adequate irrigation (Musick et al., 1976), and an early cutoff date, perhaps by deleting the last seasonal irrigation. The delayed startup probably should not be practiced if early season irrigation is needed to rewet the profile in the absence of preplant irrigation and inadequate profile wetting by precipitation.

RULE 5. Consider the need for preplant irrigation.

Preplant irrigation is a common practice in the Southern High Plains for summer row crops. It accomplishes different objectives including wetting the soil profile, germinating crop volunteer and weeds that can be killed by tillage before planting, and providing adequate seed zone soil physical condition and water contents to facilitate planting and stand establishment (Musick, 1987). As the first irrigation following primary tillage, water intake in furrow systems is frequently excessive for rewetting the profile. In tests on Pullman clay loam at Bushland, intake depths are mostly about 50 to 100% greater during the first irrigation following primary tillage than for seasonal irrigations and the high intake increases losses to deep percolation.

Storage efficiency of the preplant irrigation measured as increased profile storage at planting averages only about 20 to 40% (Musick et al., 1971; Undersander and Regier, 1987). Primary tillage is usually performed soon after October harvest for continuous grain sorghum and preplant irrigation is applied sometime between November and early May before planting in late May. Preplant irrigation that largely recharges the soil profile greatly reduces additional profile storage from precipitation between the preplant irrigation and planting (Musick et al., 1971).

A summary of preplant irrigation tests with grain sorghum at Bushland indicated that the yield response averages much lower than from seasonal irrigations (during 7 years of tests, 240 lb/ac-in. for preplant irrigation vs. 400 lb/ac-in. for seasonal irrigations, Musick, 1987). In a recent 4-yr. test by Allen and Musick (1988), eliminating the preplant irrigation delayed planting in two of the four years from mid-May to mid-June. In one year, the delayed planting failed to complete grain filling before being killed by a record early freeze (Sept. 20, 39 days earlier than normal) which reduced yields by about 10%. Eliminating the preplant irrigation reduced average water application in graded furrow tests by 9.8 in., reduced intake by 7.5 in., and grain yields by 950 lb/ac. This study confirmed results from previous tests in general that the yield response from preplant irrigation is low compared with response to seasonal irrigations.

In the tests on Pullman clay loam at Bushland, preplant irrigation only resulted in sorghum yields averaging 40% of adequately irrigated yields, Table 3. On a deeper site of the same soil series at Clovis, New Mexico, preplant irrigation only yields averaged 54% of adequately irrigated yields. At three locations in western Kansas (Garden City, Tribune, and Colby), preplant irrigation only yields averaged from 57% to 95% of adequately irrigated yields. All five test sites have largely similar seasonal precipitation amounts that average about 8 to 10 inches.

Yield results from the five test sites ranging from Clovis, New Mexico, to Colby, Kansas, indicate that when preplant irrigation yields are low compared with adequate seasonal irrigation, the yield response to seasonal irrigation is relatively high. The reverse is true also. As preplant irrigation only yields on high water storage soils are relatively high compared with adequately irrigated yields, the yield response to seasonal irrigation is relatively low which offers greater opportunity for the successful practice of deficit seasonal irrigation. An example of the excellent response to deficit seasonal irrigation for sorghum is illustrated in Fig. 5 as seasonal water application was reduced in tests at Colby on Keith silt loam (Bordovsky and Hay, 1975). This effect is shown to a lesser extent from tests at Garden City on Richfield clay loam, illustrated in Fig. 2.

Water intake during preplant irrigation frequently exceeds profile storage capacity and losses occur during the irrigation as saturated flow below the root zone. In addition, substantial slow profile drainage can occur as unsaturated flow in the absence of root extraction on the deep silt (loess) profiles in western Kansas. Profile drainage losses in tests at Tribune were measured in the 2 to 3-in. range over an extended time period (Stone et al., 1987). I also measured similar profile drainage losses in tests at Garden City over about a 4-week period following preplant irrigation on the deep silt profile of Richfield clay loam (unpublished data).

Stone et al., (1980) concluded "that the most efficient use of irrigation water is made when water is applied as close as possible to the time of plant need." By delaying the initial irrigation for wetting the profile to a growth period of substantial water use, uptake of water by roots lowers the profile water content and slows unsaturated flow during a period following irrigation and thus reduces losses to profile drainage.

RULE 6. In furrow systems, consider management for reducing water applied and field runoff.

In managing deficit irrigation, large individual irrigation applications should be reduced in amount to reduce losses to deep percolation and tailwater runoff and leave some additional profile storage capacity for precipitation occurrence following irrigation. Also, large applications will tend to leave more unused profile water storage after harvest which limits precipitation storage between harvest and planting.

Practices to reduce water intake in graded furrows are (1) the use of wide-spaced and alternate furrow irrigation, including skip-row planting and irrigation of fewer furrows than crop rows, (2) tractor wheel compaction of furrows, (3) surge-flow application, and (4) reducing or eliminating field runoff, both from irrigation and precipitation.

Wide-Spaced and Alternate Furrow Irrigation

In the Southern High Plains, conventional furrow spacing is mostly 30 or 40 in. and tests with alternate and wide-spaced furrows are mostly 60 or 80 in. Field tests with several crops at Bushland have resulted in alternate and wide-spaced furrows reducing water intake by 13 to 33% on Pullman clay loam (Musick and Dusek, 1974) and at Goodwell, Oklahoma, by 16 to 20% on a 1/2 mile field length of Richfield clay loam (Stone et al., 1982). In general, yield response to reduced intake using wide-spaced and alternate furrow irrigation has been favorable (Crabtree et al., 1985; Musick and Dusek, 1974; Stone et al., 1979 and 1982). In irrigation of summer row crops, crop rows should have one side adjacent to an irrigated furrow to prevent excessive water deficits by row isolation from an irrigated furrow by an intervening row or rows.

In deficit irrigation tests at Bushland, we normally limit tailwater runoff to about 10% or less of water applied or about 1/2 of the runoff normally allowed during adequate irrigation tests. In the deficit irrigation tests conducted in graded furrows, yield reductions are mostly concentrated on a lower field section (about 1/4 to 1/3 of the field length). Lower field water intake and yield can be improved without increasing tailwater runoff time and amount by deeper than normal tillage of the lower field section that would normally show reduced yield (Musick et al., 1981). In using chisel tillage after harvest to the 8-in. depth, I have increased water intake on the lower 1/3 of a 1900-ft field length on Pullman clay loam by using a second pass with loosening to the 12-in. depth. This practice is preferred to deep tillage of the entire field which can result in excessive water intake during irrigation.

Wide-spaced furrows are used in wide bed-furrow systems. These systems allow wheel traffic to be maintained on a wide bed if desired (Allen and Musick, 1972; Allen, 1985). Wide-spaced and alternate furrow irrigation systems that partially wet the surface soil and the profile reduces surface evaporation losses following irrigation and provides some additional storage capacity for rainfall. Furrow dams can be used in nonirrigated furrows to minimize storm runoff (Stewart et al., 1983). Conventional every furrow irrigation results in nonuniformity of water application between wheel track and nonwheel track furrows with excessive runoff from the wheel track furrows or require additional time for adjusting furrow flow rates. Wide bed-furrow systems that maintain wheel tracks on the beds avoid this problem.

Tractor Wheel Compaction of Furrows for Intake Control

Furrow compaction by tractor wheels were used to effectively reduce excessive irrigation water intake in tests on Olton clay loam in the Texas High Plains (Musick et al., 1985; Musick and Pringle, 1986). A tractor wheel pass was used in 60-in. spaced furrows to increase a 3-in. furrow bottom density zone from a loose soil condition by tillage to about 1.6 g/cc and reduce water intake on a 1/4-mile furrow length by 33% and deep percolation by one-half. Irrigations were applied at about 50% profile soil water depletion and the reduction in intake more closely balanced intake quantity with profile storage capacity. Corn yields were not reduced when compared with irrigation of nonwheel track furrows only on 60-in. spacing. The tractor wheel furrow compaction was removed by primary tillage after harvest.

The first irrigation after primary tillage on the clay soils normally is the most excessive for intake compared with seasonal irrigations. In a 4-yr. test completed at Bushland in 1988, Allen and Musick used tractor wheel traffic in furrows to successfully reduce water intake during a preplant irrigation and a chisel furrow ripping operation immediately preceding the first seasonal irrigation to largely restore normal furrow intake during seasonal irrigations. Intake studies using a flowing furrow infiltrometer indicated the potential during a 4-hr. test period for reducing intake by one-half following tractor wheel compaction.

Surge-Flow Irrigation

Surge-flow is the practice in the High Plains of using an available water supply from wells applied through gated pipe to a larger area than is irrigated in a conventional flow irrigation set by alternating water inflow surges to a set of furrows on each side of a controller-valve assembly. Surging of the flow in on-off cycles is effective in reducing water intake rates with the greatest effect occurring when the surface soil is in a loosened condition by tillage. The intake reduction is substantially reduced when the surface soil is consolidated from wheel traffic, from the effects of tillage implements, or from previous irrigation. Thus, the beneficial effect is greatest during the first irrigation following primary tillage such as preplant or emergence irrigation and to a lesser extent during the first seasonal irrigation when the surface soil is in a loosened condition following cultivation of row crops. The beneficial effect is reduced during irrigation of wheat because of the retarding effect of wheat vegetation in the furrows on the surge advances over previously wetted furrow sections.

During seasonal irrigations of clay soils when effects on intake are small, the benefit from surge-flow is more likely to be related to managing reduced tailwater runoff. Surge-flow can be managed for near continuous tailwater runoff by using a short cycle time during the runoff phase in which surge advances tend to catch up with recession flow on lower field sections. Also, a surge valve has potential for automating a nighttime set change of a continuous flow set on one side of the valve to a continuous flow set on the other side. Sets that need a nighttime change are usually allowed to run until early morning which can greatly increase tailwater runoff losses.

In comparing effects of surge-flow application to nonwheel track furrows only with furrow compaction from a tractor wheel on Olton clay loam, both were effective in reducing excessive water intake (Musick and Pringle, 1986; Musick et al., 1987). In these tests, surge-flow was managed to reduce cumulative water intake during seven irrigations for corn in a dry season from 39.1 in. for continuous flow irrigations to 28.9 in. without reducing yields. Tailwater runoff was reduced from 7.4 in. for continuous flow to 3.2 in. with surge-flow. Intake reduction was 32% when the soil was in a loosened condition from tillage and averaged 17% for seasonal irrigations when the surface soil was reconsolidated by previous irrigation.

Management of surge-flow on the slowly permeable Pullman clay loam at Bushland has been less successful for reducing intake than test results on moderately permeable Olton clay loam. A reason for the reduced effect on Pullman clay loam is believed to be the influence of shrinkage crack zones on water intake on this soil and the likelihood that surge-flow has very little effect on reducing water intake through cracks. The Olton clay loam has about 10% lower B horizon clay content than Pullman clay loam and develops very low shrinkage crack volume during profile drying.

Reducing or Eliminating Field Runoff

Deficit irrigation is practiced in graded furrow systems to reduce and sometimes to eliminate tailwater runoff during irrigation of crops having drought resistance. In recent years, as irrigation wells have declined in yields and pumping costs have increased, farmers in the Southern High Plains have reduced tailwater runoff from about the 30 to 40% range of water applied when pumping costs were low to about 15 to 20% in recent years (Musick and Walker, 1987). About 60% of the furrow irrigated area is on slowly permeable swelling clays (Musick et al., 1988). The large crack volume following profile drying of these soils causes rapid initial intake of about 30 to 40% of the the total irrigation intake volume. After initially filling the crack volume and wetting the surface soil layer, intake rates (largely controlled by the $B2_t$ horizon below normal tillage depth) decline rapidly after about 3 to 4 hours to about 0.1 in./hr. The low basic rate limits the additional intake volume and yield response from extended duration of tailwater flow. In tests of differential tailwater runoff for grain sorghum, Schneider et al. (1974) found very little yield response from extending tailwater runoff time beyond a 3 to 4-hr. period to a 6 to 8-hr. period in 24-hr. irrigation sets. However, when no tailwater runoff was allowed, significant lower-field yield reductions occurred.

The tests by Schneider et al. (1976) and a previous test by Musick et al. (1973) on the same 1800-ft. field length site indicated that irrigation of slowly permeable swelling clays in graded furrow systems can be managed to mostly limit tailwater runoff to less than 10%. Although lower field deficits occurred, the reduced water intake on the lower field sections resulted in increased irrigation water use efficiencies for grain production, illustrated in Fig. 6. In this test, seasonal precipitation contributed significantly to the uniformity of yield with length of run, minimizing the yield effect of the intake nonuniformity.

The increased irrigation water use efficiency values associated with reduced lower field intake depths were substantiated in a 3-yr. level border test for grain sorghum. Reducing total application by one-half by reducing individual applications from 4 to 2 in. increased average irrigation water use efficiencies from 335 lb/ac-in. to 511 lb/ac-in. for nine treatment-years of data (Musick and Dusek, 1971). In these tests, seasonal precipitation contributed also to the favorable yield response to reduced application and is considerably greater than would be expected in major dry seasons.

Stewart et al. (1983) developed and successfully tested a limited irrigation-dryland (LID) system on Pullman clay loam for preventing irrigation tailwater and storm runoff from leaving a field. Water was applied for grain sorghum to fully irrigate the upper one-half of a 1900-ft. field length. Tailwater from the fully irrigated section was utilized on the next one-fourth field section, and the lower one-fourth field section was dryland sorghum with furrow dams to retain and utilize precipitation and thus prevent storm runoff. Irrigation was applied to alternate 30 in. furrow spacing and furrow dams were maintained for the complete field length of the alternating nonirrigated furrows.

During the 3-yr. test, irrigation tailwater and storm runoff from conventional graded-furrow irrigation of 30-in. furrow spacing, averaged 7.0 in. while total runoff from the LID system averaged 0.3 in. Irrigation water use efficiency values without a reuse system in the conventional test averaged 208 lb/ac-in. while the LID systems averaged 308 to 385 lb/ac-in. (Stewart et al., 1983). The success of the LID system for sorghum production was enhanced by a planter modification that permitted on-the-go seeding rate changes to reduce plant densities on the tailwater and dryland sections.

RULE 7. Consider modifying some cultural practices.

Modification of cultural practices used for adequate irrigation primarily involves use of conservation tillage, moderate plant densities, flexible planting dates, shorter maturity sorghum hybrids (dryland types), and some use of cropping systems involving fallow for increased precipitation storage between crops.

Deficit irrigation places greater emphasis on efficient use of resources for production and conservation tillage (including no-tillage) that involves management of crop residues on the surface for increased precipitation storage is used to a greater extent. A successful system tested at Bushland has been the use of no-tillage and chemical weed control following deficit irrigation of wheat and no-till seeding of sorghum about 11 months later with the sorghum grown under deficit irrigation (Musick et al., 1977). The no-till management during fallow after wheat is effective in increasing precipitation storage and eliminating the preplant irrigation for sorghum. The system has two crops in three years with 11 months of fallow between harvest and planting of each crop.

In the Southern High Plains, corn is seeded about one month earlier than sorghum and the system is currently under test at Bushland for corn production without preplant irrigation. An additional tillage treatment involves application of atrazine plus 2,4-D after harvest in combination with a fall sweep tillage operation for late summer grass control and surface layer loosening to facilitate later seeding of corn. The corn is flat seeded and water furrows opened prior to the first seasonal irrigation.

Other cropping systems that have been successfully tested for efficient use of deficit irrigation are (1) alternating equipment-width field strips of wheat and sorghum combined with wide-spaced furrow irrigation with the outside crop rows benefiting from a border effect during the nongrowing period of the adjacent crop (Musick and Dusek, 1972 and 1975), (2) double cropping combined with no-till seeding (Allen et al., 1975; Musick et al., 1977), and (3) combination of limited irrigation with dryland systems (Stewart et al., 1983; Unger and Wiese, 1979; Unger 1984).

The use of moderate plant densities may be desirable for crops that do not tiller extensively to limit interplant competition for water and allow more gradual development of water deficits. Use of moderate densities for sorghum increases early season tiller initiation and tillers that mature heads are an important regrowth contribution to yield ability when stress during boot stage reduces head size and seed numbers per head. Use of moderate plant densities is of lesser importance for wheat because of tiller compensation when plant density is reduced. If narrow row culture is used for adequate irrigation, row spacing does not need to be changed for deficit irrigation (Musick and Dusek, 1969).

Skip-row planting and irrigation of fewer furrows than crop rows has been tested for sorghum and corn (Musick and Dusek, 1982) and for cotton by Newman (1967). The most common system is planting two 30 or 40-in. rows and leaving one row unplanted and irrigating the one furrow between two crop rows. This practice is very effective in reducing average irrigation depth in graded furrows. It is widely practiced for cotton in the more limiting groundwater areas of the south Texas High Plains. Although irrigation water is used very efficiently, precipitation is used less efficiently because of increased evaporation losses from the bare soil areas separating the paired crop rows.

In the Southern High Plains, planting dates are more flexible for deficit irrigation of grain sorghum and involve using a wider range of maturity-length hybrids. Under adequate irrigation, longer maturity hybrids are normally planted by mid-May for high yields while shorter maturity dryland types are planted anytime from about mid-May to mid-June for deficit irrigation management. The dryland-type hybrids in general have superior drought resistance and delayed planting enhances stand establishment without preplant irrigation.

Table 1. Average grain sorghum yield increase and irrigation water use efficiency, Etter, Texas, 1969 and 1972. Data from Shipley and Regier, 1975.

	Stage of Development When Irrigated			
	6-8 leaf	Mid- to late-boot	Heading to flowering	Milk to soft dough
<u>Grain yield increase per irrigation - lb/acre</u>				
1969	342	2,388	2,550	254
1972	499	1,096	1,708	696
<u>Irrigation water use efficiency - lb/acre-inch</u>				
1969	86	597	637	64
1972	125	274	427	174

Table 2. Average 2-year (1969 and 1972) irrigation use efficiency from one 4-inch seasonal irrigation when the total number of seasonal irrigations ranged from 1 to 4. Data from Shipley and Regier, 1975.

Number seasonal irrigations	Stage of Development When Irrigated			
	6-8 leaf	Mid- to late-boot	Heading to flowering	Milk to soft dough
	lb/acre-inch			
1	0	505	481	23
2	90	460	545	122
3	156	386	536	137
4	208	404	537	150

Table 3. Preplant only irrigated sorghum grain yield as a percent of adequately irrigated yields, for different locations and soils in the Central and Southern High Plains.

Location	Soil	No. of Test Years	Preplant only yield as % of Adequate Irrigation	Data Source
Bushland, TX	Pullman clay loam	7	40	Musick, 1987
Clovis, NM	Pullman clay loam	3	54	Finkner and Malm, 1971
Garden City, KS	Ulysses clay loam	8	57	Erhart, 1970
Garden City, KS	Richfield clay loam	6	66	Musick and Grimes, 1961
Garden City, KS	Richfield silty clay loam	6	79	Hooker, 1985
Tribune, KS	Ulysses silty clay loam	3	81	Stone et al., 1978
Colby, KS	Keith silt loam	3	95	Bordovsky and Hay, 1975

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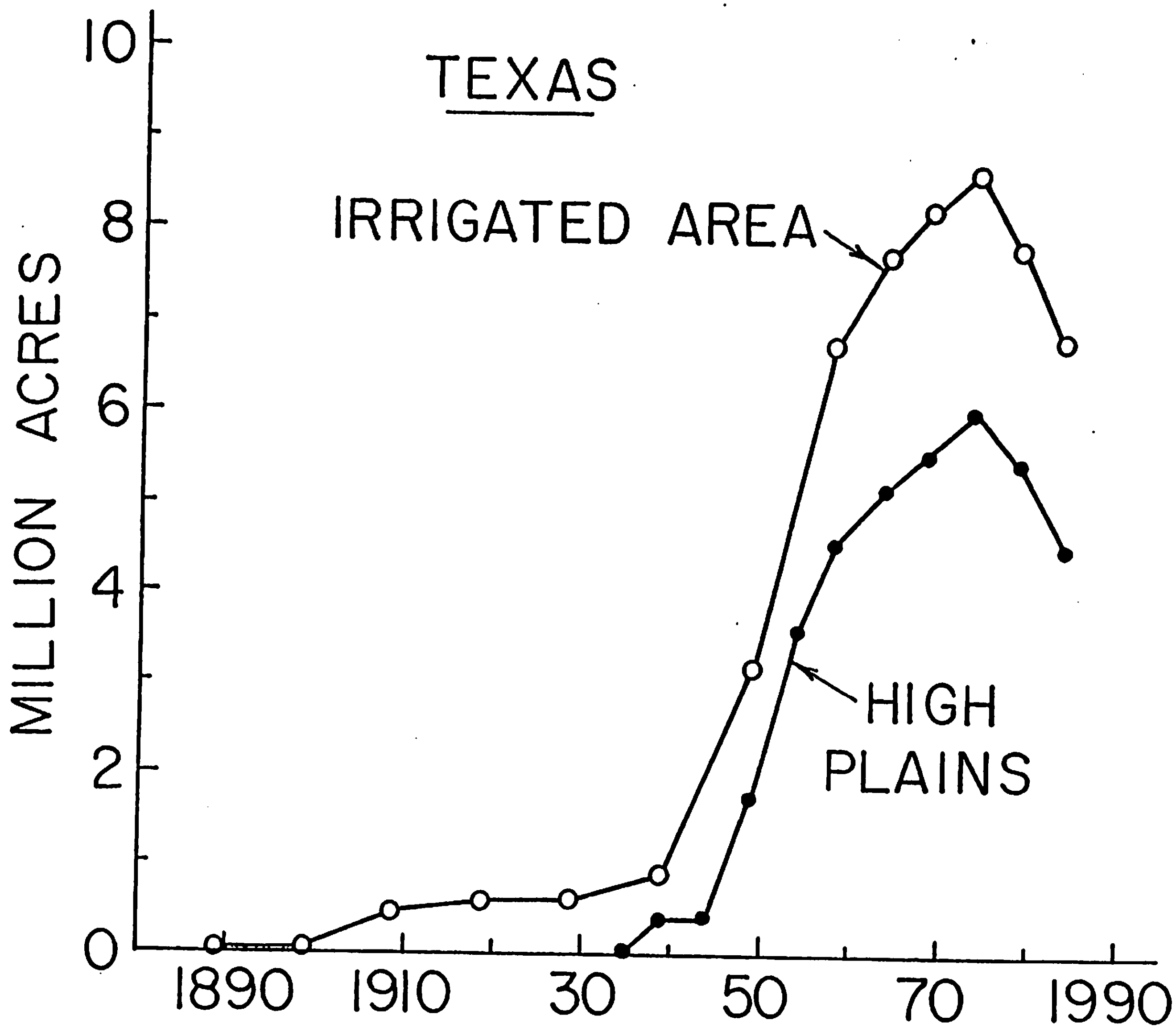

Fig. 1. Total irrigated area in Texas and in the Texas High Plains. Data sources: for Texas through 1949, U.S. Agricultural Census; for the High Plains through 1954, Texas Agricultural Extension Service; since 1958, county inventory reports of irrigation in Texas, Soil Conservation Service and Texas Water Development Board (Musick et al., 1988).

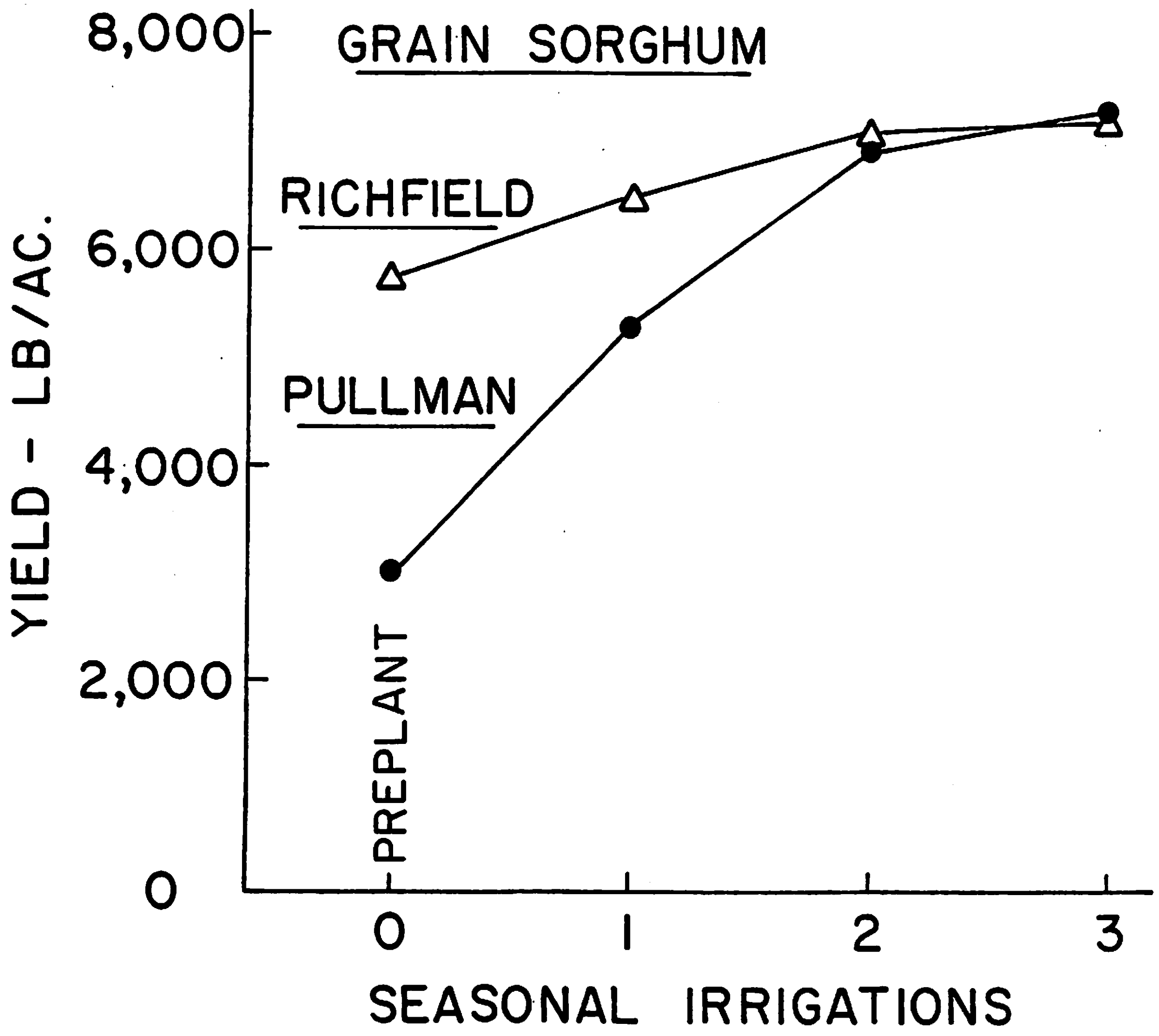

Fig. 2. Average 3-year response to 1, 2, and 3 well-timed seasonal irrigations on Richfield clay loam, Garden City, KS, and Pullman clay loam, Bushland, TX. (Adapted from Musick and Sletten, 1966).

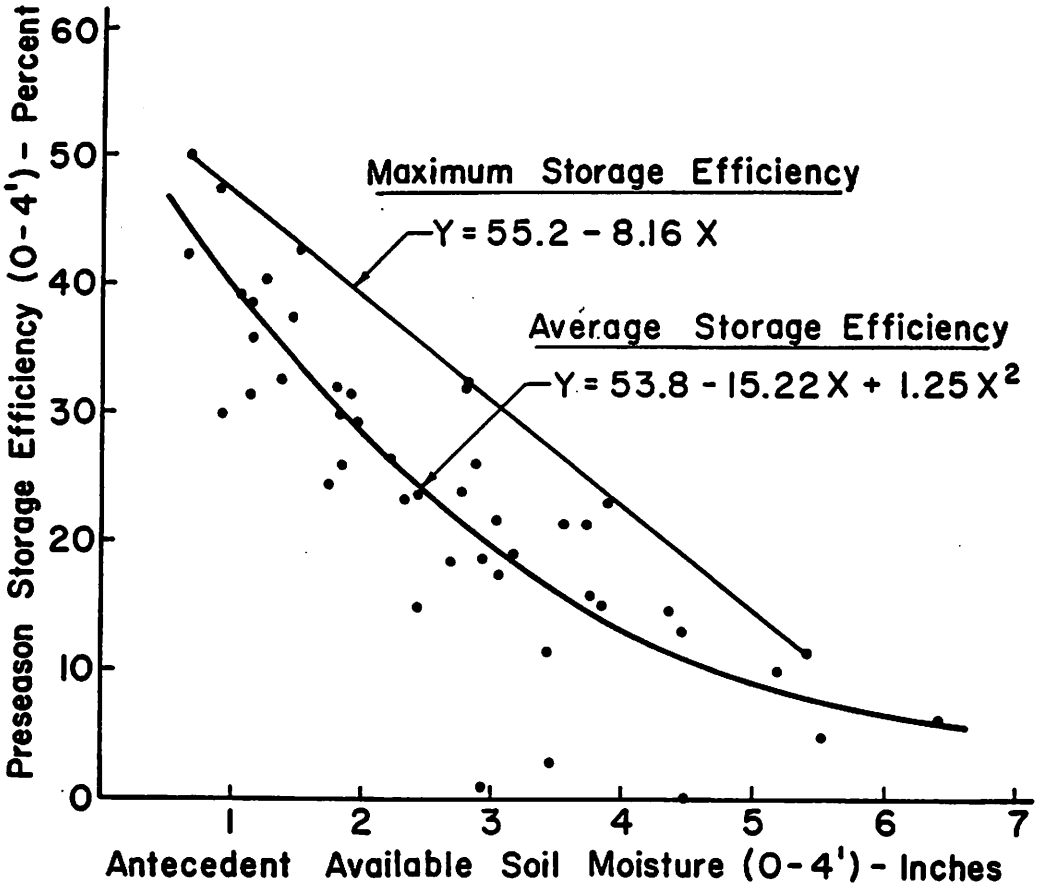

Fig. 3. Effect of available soil water storage after harvest on preseason precipitation storage efficiency, to 4-foot depth, Pullman clay loam, Bushland, TX, (Musick, 1970).

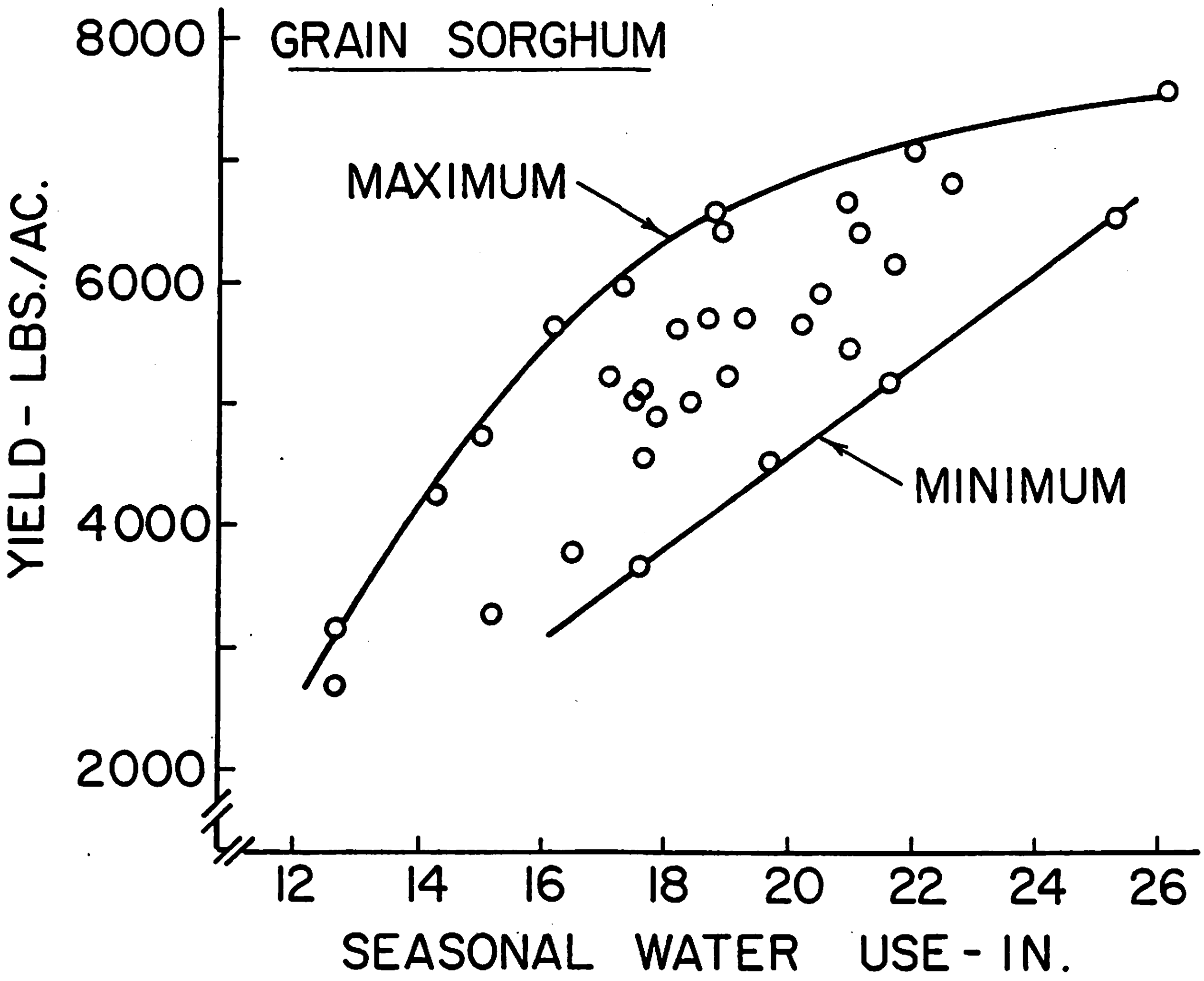

Fig. 4. Seasonal water use-grain yield relationship for grain sorghum grown on Pullman clay loam, Bushland, TX. The range of grain yield for a given level of seasonal water use was primarily related to number, timing and size of seasonal irrigations (Musick and Dusek, 1971).

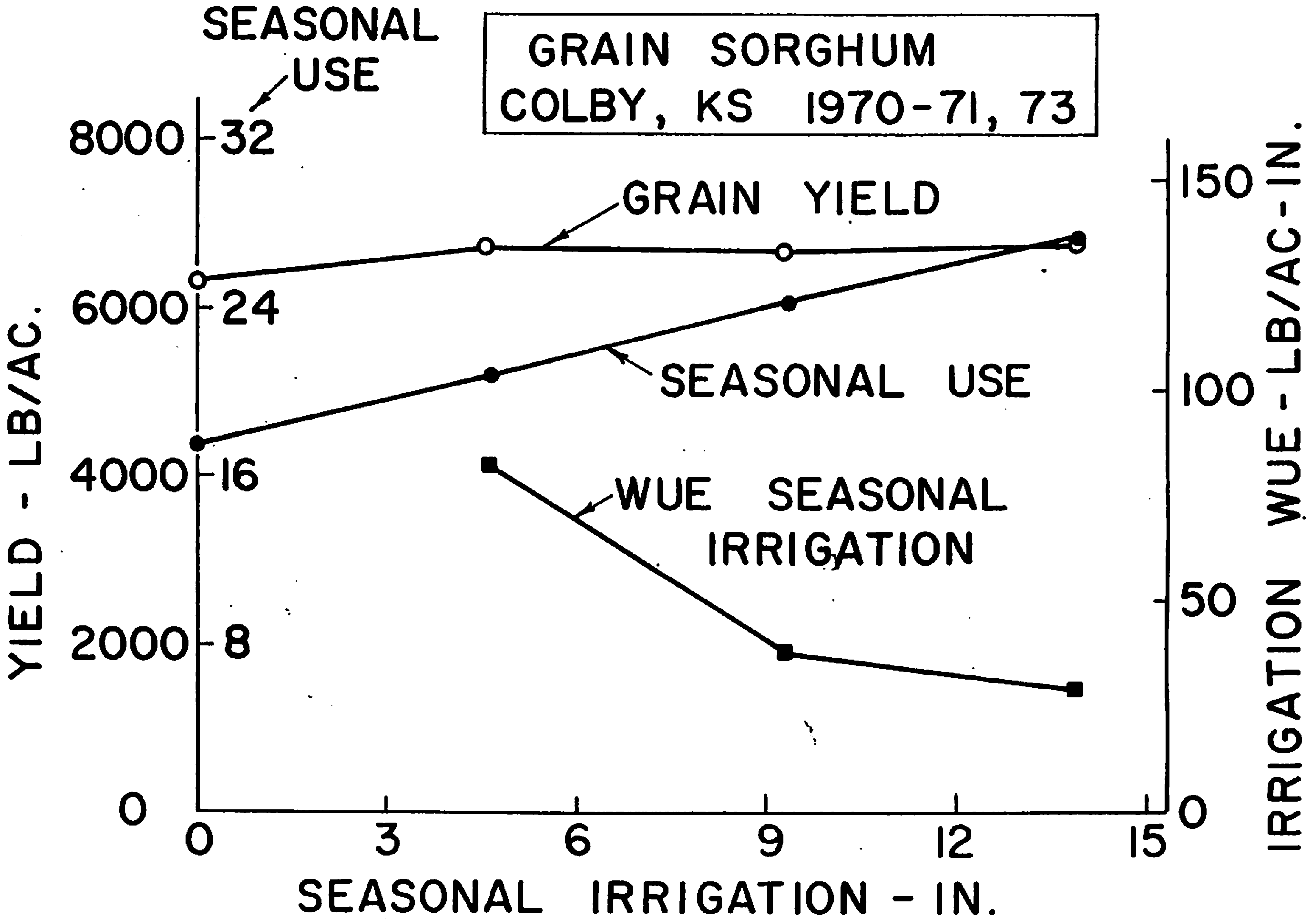

Fig. 5. Yield, seasonal water use and irrigation water use efficiency of grain sorghum response to seasonal irrigation, Keith silt loam, Colby, KS. (Adapted from Bordovsky and Hay, 1975).

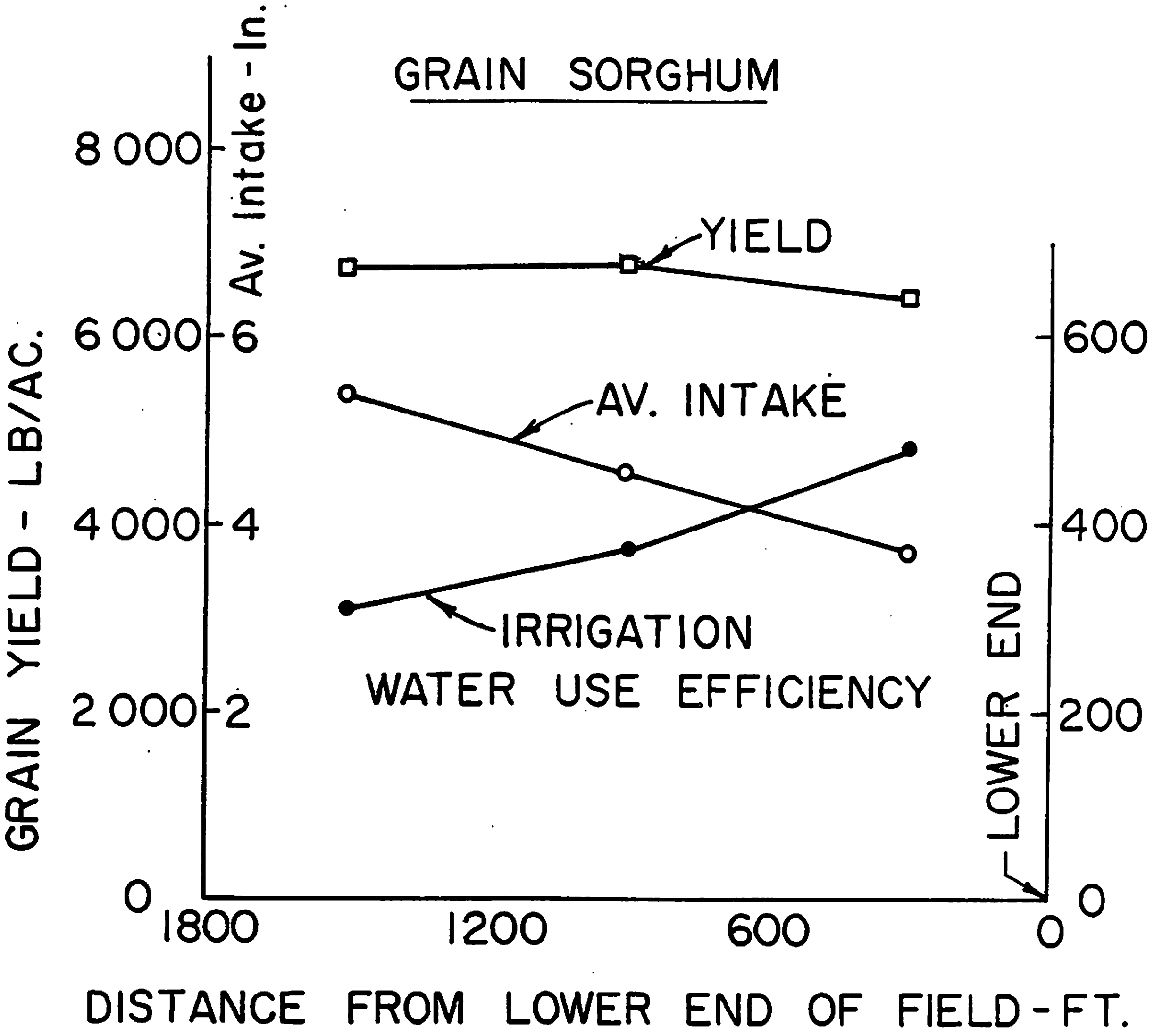

Fig. 6. Effect of distance down the field on graded furrow water intake, sorghum yield and irrigation water use efficiency, Pullman clay loam, Bushland, TX. (Adapted from Musick et al., 1973).