Factors Related to Dryland Grain Sorghum Yield Increases: 1939 through 1997

Paul W. Unger* and R. Louis Baumhardt

ABSTRACT

Grain yields of dryland (nonirrigated) grain sorghum [*Sorghum bicolor* (L.) Moench], a major crop in the southern Great Plains, more than tripled in studies at the USDA-ARS Conservation and Production Research Lab., Bushland, TX, during the period from 1939 to 1997. Our objectives were to document the yield increases that occurred and to determine factors primarily responsible for the yield increases. Factors evaluated were annual precipitation, growing-season rainfall, soil water content at planting, soil water use, growing-season evapotranspiration, and year of record. For the report, we assembled 502 treatment-years of grain yield data from 37 studies. For the 1939–1997 period, grain yields increased about 50 kg ha^{-1} annually. Yields increased 139% during the 1956–1997 period, with 46 of those percentage units resulting from use of improved hybrids, based on results of a uniformly managed 40-year study. The remaining 93 percentage units for that period were attributed to other factors, primarily to soil water at planting. Increases in soil water at planting resulted from changes in management practices with time, mainly the adoption of improved crop residue management practices after about 1970.

Grain sorghum, a well-adapted crop for the southern Great Plains of the United States, is grown extensively under irrigated and dryland (rainfed) conditions. When full irrigation is supplied to meet crop water needs, sorghum grain yields of up to 8000 kg ha^{-1} are common (Allen and Musick, 1990, 1996; Allen et al., 1980; Jensen and Sletten, 1965; Musick and Dusek, 1971, 1972), and even greater yields have been obtained. In contrast, dryland sorghum is strongly influenced by plant-available soil water content at planting (Jones and Hauser, 1975) and by growing-season rainfall, especially in the semiarid western portion of the southern Great Plains. Adequate soil water or rainfall for timely planting, together with favorable growing-season rainfall, allow for good yields of dryland sorghum. However, soil water storage; rainfall timeliness, amount, and distribution; other climatic conditions (for example, first freeze date in fall); and crop management practices are highly variable. Consequently, grain yields of dryland sorghum often are highly variable, ranging from near or complete failures to as much as 6000 kg ha^{-1} (Jones and Johnson, 1991; Sow et al., 1996; Unger, 1978, 1988, 1992).

Extensive research has been conducted at various locations in the southern and central Great Plains to develop improved practices for irrigated and dryland grain sorghum production. Included are more than 30 studies involving the crop on dryland at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, in the southern Great Plains. Our objectives were to (i) document the increases in dryland sorghum grain yields that have occurred through the years in studies at the Laboratory and (ii) identify factors primarily responsible for the yield increases. Yield trends for irrigated sorghum are not included in this report.

MATERIALS AND METHODS

Crop Performance Data

Data for this report are from past or ongoing research conducted from 1939 through 1997 at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX. Bushland is at 35°11′ N lat and 102°5′ W long and 1180 m above mean sea level. All studies were conducted on Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll), the dominant soil at the Laboratory. For this report, we assembled yield data from 37 separate research projects with a total of 502 treatment-years. The published reports from which data were taken are included in the reference list, identified by an asterisk. Studies currently in progress are listed in Table 1.

Treatments for these projects involved different cropping systems (continuous and rotations), tillage methods (clean, stubble mulch, ridge, and no-tillage), mulch rates, plant populations, hybrids, and nonirrigated controls from several irrigation studies. The wide diversity of treatments resulted in highly variable grain yields within and among years. A cursory examination of all data (Fig. 1), however, revealed that sorghum grain yields more than tripled during the period of record. More data were available for some years than for others; therefore, to reduce scatter and the potential for bias, we calculated annual mean yields (AVYLD, kg ha^{-1}) and used them for the analyses. Minimum and maximum sorghum yields (MINYLD, kg ha^{-1}; MAXYLD, kg ha^{-1}) also tended to increase and were evaluated, when available, after 1956. Possible reasons for the yield increases included improvements of cultivars and hybrids, pest control (weeds and insects), and cultural management practices. Our analyses included data on annual precipitation (ANPRCP, mm), growing-season rainfall (GSPRCP, mm), plant-available soil water content at planting (SWPLNT, mm), growing-season soil water use (SWUSE, mm; content at planting minus content at harvest), and growing-season evapotranspiration (GSET, mm; SWUSE plus GSPRCP) from reports or studies for which this information was available. When this was not available, we estimated growing-season rainfall (June–October) based on rainfall records at the Laboratory or from other studies conducted at the same time. We also estimated soil water content at planting and soil water use data from other studies conducted under similar conditions in the same years. For studies considered for this report, fertilizers were not applied because dryland sorghum has not responded to fertilizer on Pullman soil. Greater use of fertilizers, however, has resulted in greater yield of many crops since the 1950s at other locations.

Methods of Analysis

We used Pearson correlation procedures (Haan, 1977; SAS Inst., 1988) to identify relationships among years of record

USDA-ARS, Conservation and Production Res. Lab., P.O. Drawer 10, Bushland, TX 79012. Received 23 Nov. 1998. *Corresponding author (pwunger@ag.gov).

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Abbreviations: ANPRCP, annual precipitation; AVYLD, annual mean yield; GSET, growing-season evapotranspiration; GSPRCP, growing-season rainfall; MAXYLD, maximum yields; MINYLD, minimum yield; SWPLNT, soil water content at planting; SWUSE, soil water use; YEAR, year of record.

Table 1. Studies at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, from which data were obtained for this report.

Study	Conditions	Years†
Conservation bench terrace system under dryland conditions	Wheat–sorghum–fallow rotation; stubble mulch tillage and no-tillage	1958–1997
Dryland no-tillage	Wheat–sorghum–fallow rotation	1985–1997
Residue management and paratillage	Wheat–sorghum–fallow rotation; stubble mulch and no-tillage; with and without paratillage	1991–1995
Profile modification	Modified to 0-, 0.9-, and 1.5-m depth; stubble mulch tillage	1992–1997; no crop in 1996
Surface residue enhancement	Wheat–sorghum–fallow rotation; no-tillage; five wheat varieties and five sorghum hybrids	1995–1997
Cropping systems	Wheat–sorghum–fallow and continuous sorghum; no-tillage	1995–1997; no crop in 1996

† Studies were still in progress at the time of the present work. Published sources of data are given in the reference list, marked with an asterisk.

(YEAR), grain yield, rainfall, soil water content and use, and evapotranspiration variables. These preliminary analyses were used to identify those factors that were correlated with crop performance or that duplicated information (intercorrelated). Correlations were computed first on the entire 1939–1997 data set for those parameters that appeared throughout the period of record and then for the more complete 1956–1997 data set. Analyses of these variables in either data set had only a minor effect on the interpretation obtained. We therefore used the more complete 1956–1997 data set (including occasional estimated soil water content and water use values) in the rest of our analyses. An additional subset for crop performance during the 1970–1997 period was analyzed to evaluate the impact of improved residue management practices on yield and water use parameters.

Both simple and multiple linear least square regression models were developed to determine which factors or combinations of factors were related to the long-term grain yield increases. These models excluded intercorrelated factors and included yield-affecting factors previously identified in the correlation analyses. Multiple-factor regression models were developed in a stepwise manner; that is, factors correlated with yield were introduced or retained in the yield model, provided such action significantly ($P = 0.05$) increased the coefficient of determination, R^2. Differences between observed and model-predicted yields were further analyzed to identify conditions when the model failed.

RESULTS AND DISCUSSION

Year Effects on Grain Yields and Water Variables

Preliminary correlation of yield with available AVYLD, YEAR, ANPRCP, and GSET data was calculated for the 59-year period of record (1939–1997). The AVYLD steadily increased during this period and was positively ($P = 0.01$) correlated with YEAR ($r = 0.63$). Although this correlation has no biological basis, it illustrates the increases in grain yields that have occurred through the years, which was our first objective. Mean grain yields increased 348% (from 840 to 3760 kg ha^{-1}) during the 1939–1997 period (Fig. 2), which is comparable to the average increase for sorghum in the United States from 1930 to 1990 (Eghball and Power, 1995). The temporal variability was greater in this study because the results were only for a semiarid location, whereas the average increase for the entire country was based on results from numerous locations.

After determining that yields significantly increased with time, it was necessary to determine whether ANPRCP or GSPRCP also had changed during the period of record. Both ANPRCP and GSPRCP describe climatic factors and, therefore, should be independent of (not correlated with) the year of observation. While these two variables were highly intercorrelated ($r = 0.74$) (i.e., they contained similar information about precipitation), they were not correlated with year of observation. Sorghum grain yields increased during this 59-year period, but precipitation did not increase correspondingly. Yearly precipitation amounts for 1939 through 1997 are given in Fig. 3. Growing-season rainfall averaged 270 mm and total annual precipitation (growing season plus non-growing season) averaged 475 mm, but both were highly variable among years. For example, growing-season rainfall ranged from 76 mm in 1940 to 503 mm in 1960 and total precipitation (including the water equivalent of snow) ranged from 240 mm in 1970 to 828 mm in 1941.

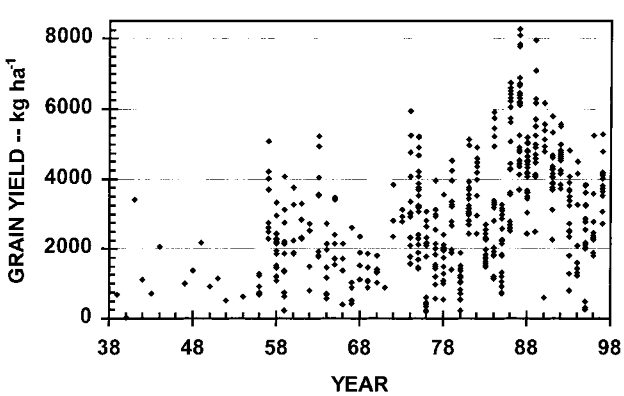

Fig. 1. Grain yields for dryland grain sorghum in studies conducted at the USDA-ARS Conservation and Production Res. Lab., Bushland, TX (1939–1997).

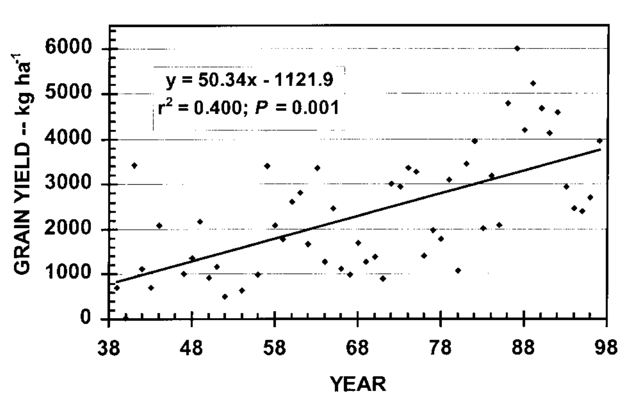

Fig. 2. Average annual grain yields for dryland grain sorghum in studies conducted at the USDA-ARS Conservation and Production Res. Lab., Bushland, TX (1939–1997).

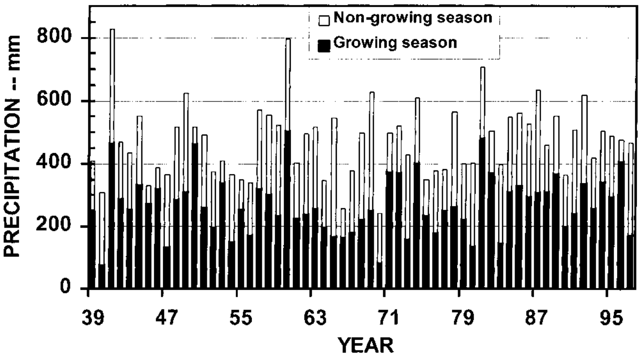

Fig. 3. Precipitation during the grain sorghum growing season and non-growing season at the USDA-ARS Conservation and Production Res. Lab., Bushland, TX (1939–1997). The growing-season plus non–growing-season amounts indicate the total for each year.

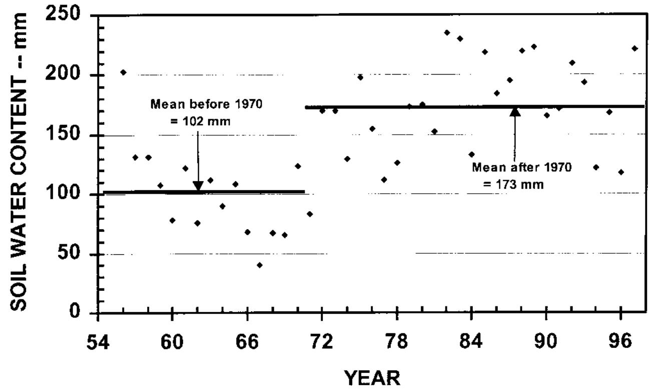

Fig. 4. Average annual volumetric soil water content at planting time for dryland grain sorghum in studies conducted at the USDA-ARS Conservation and Production Res. Lab., Bushland, TX (1956–1997).

Beginning with 1956, more complete production information was available. Included was a range of annual yields, which allowed establishment of a data set that contained annual minimum (MINYLD) and maximum yields (MAXYLD). More complete information was available also for SWPLNT, SWUSE, and GSET (i.e., SWUSE plus GSPRCP). The correlation coefficients for all factors for the 1956–1997 period are shown in Table 2. For the 1956–1997 period, average yields increased 139% (from 1600 to 3830 kg ha^{-1}), minimum yields increased 91% (from 1040 to 1990 kg ha^{-1}), and maximum yields increased 127% (from 2500 to 5680 kg ha^{-1}). The minimum yields included several crop failures because of drought or freezing temperature before crop maturity. The maximum yields included results from rotation studies in which dryland sorghum followed irrigated winter wheat (*Triticum aestivum* L.) after about 300 d of fallow (Unger, 1984; Unger and Wiese, 1979). Average, minimum, and maximum annual yield factors are, as expected, intercorrelated ($r = 0.59$ to 0.93), with both AVYLD and MAXYLD correlated with YEAR ($r = 0.53$ and 0.56, respectively). All results clearly showed that sorghum grain yields increased with time (years) during the period of record, possibly as a result of improvements in cultivars or management practices.

Introduction of improved cultivars and hybrids or greater response of those cultivars and hybrids to improved soil water management may explain part of the long-term yield increase. Unfortunately, information on specific cultivars and hybrids used was not available for all studies. One ongoing study on conservation bench terraces, however, involved different hybrids from 1958 through 1997. Management practices have remained constant for this long-term study (40 years), which involves stubble mulch tillage and prevention of all runoff of water from the system. Runoff from the upslope, nonleveled watershed is captured on the leveled bench portion of the system (Hauser, 1968; Hauser and Cox, 1962; Zingg and Hauser, 1959). Grain yields of sorghum grown on the bench were greater than yields in other studies in 7 of the first 20 years (1958–1977), indicating that growing sorghum on the bench was a good practice during the early years. As a result, yields from this study should provide a good indication of the improvements in sorghum yields due to use of improved hybrids through the years. Grain yields for early hybrids averaged 2240 kg ha^{-1} from 1958 through 1977 and were >3000 kg ha^{-1} in only 6 of the 20 years. In contrast, yields with improved hybrids averaged 3260 kg ha^{-1} from 1978 through 1997 (1990 excluded because no yield obtained) and were >3000 kg ha^{-1} in 12 of the 19 years. The average increase was 1020 kg ha^{-1} (about 46%). The reason for the single-step yield increase was that the one hybrid used until 1978 was replaced with improved hybrids that yielded similarly in another study (Unger, 1994a). If the assumption is valid that improved hybrids resulted in this 46% yield increase, the remaining 93 percentage units of the total 139% increase for the pe-

Table 2. Correlation coefficients (*r*) for dryland grain sorghum production factors from 1956 to 1997, at Bushland, TX.

	r								
Factor†	**AVYLD**	**MINYLD**	**MAXYLD**	**YEAR**	**ANPRCP**	**GSPRCP**	**SWPLNT**	**SWUSE**	**GSET**
AVYLD	1.000	0.778***	0.929***	0.529***	0.371*	0.375*	0.583***	0.109	0.434**
MINYLD		1.000	0.594***	0.304	0.422**	0.339*	0.485**	0.223	0.478**
MAXYLD			1.000	0.561***	0.382*	0.424**	0.472**	−0.021	0.405**
YEAR				1.000	0.051	0.182	0.579***	0.181	0.227
ANPRCP					1.000	0.766***	−0.021	−0.410**	0.667***
GSPRCP						1.000	0.037	−0.439**	0.874***
SWPLNT							1.000	0.523***	0.285
SWUSE								1.000	0.001
GSET									1.000

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† AVYLD, average yield, kg ha^{-1}; MINYLD, minimum yield, kg ha^{-1}; MAXYLD, maximum yield, kg ha^{-1}; YEAR, production year; ANPRCP, annual precipitation, mm; GSPRCP, growing season rainfall, mm; SWUSE, soil water use, mm; GSET, total water use, mm.

riod must be attributed to improved management practices.

The average, minimum, and maximum yields from 1956 to 1997 were significantly correlated with SWPLNT and GSET, but not with SWUSE (Table 2). These findings suggest that management practices that increase GSET, or at least increase SWPLNT, will promote greater crop yields. The increase in SWPLNT was strongly related to the YEAR of observation during the 1956–1997 period (Fig. 4). Although mean SWPLNT increased with YEAR ($r = 0.58$) due to improvements in management practices, growing-season SWUSE and GSET did not increase with YEAR. Because neither growing-season SWUSE nor GSET increased during the period of record, the results strongly suggest more efficient use of GSPRCP when more crop residues were present on the soil surface contributed greatly to the increases in grain yields with time. The negative correlations of SWUSE with both ANPRCP and GSPRCP, which are independent of YEAR, further support the conclusion that crop residues were important for increasing yields. Greater use of GSPRCP with more crop residues on the soil surface resulted mainly from less evaporation, as shown by Lascano and Baumhardt (1996) for cotton (*Gossypium hirsutum* L.), and, to a lesser extent, less runoff.

The increase in SWPLNT during the 1956–1997 period (Fig. 4) became evident beginning in the early 1970s. Pearson correlation analyses for the 1970–1997 period showed that SWPLNT and YEAR of observation were not correlated (Table 3). That is, after 1970, SWPLNT did not increase annually. This period corresponds to the time when major changes in tillage practices were made at the Laboratory. Research before 1970 involved mainly clean or stubble mulch tillage to control weeds during the fallow period between crops. Yield results involving use of herbicides for dryland cropping generally were poor during that period (Wiese et al., 1960, 1967). A major shift to no-tillage crop production occurred in the early 1970s, but clean and stubble mulch tillage still were included in some studies. Use of no-tillage cropping maintains crop residues on the soil surface, which reduces soil water evaporation (Smika and Unger, 1986) and enhances the potential for water infiltration (Rockwood and Lal, 1974). Together with the improved weed control achieved with herbicides, these factors are largely responsible for the greater soil water conservation realized with the introduction of improved herbicides in the early 1970s. One study also involved crop residues placed on the soil surface as a mulch (Unger, 1978), which also resulted in greater SWPLNT than the no-residue treatment.

Water Variable Effects on Grain Yield

Average, minimum, and maximum yields increased steadily during the 1956–1997 period due to improved water conservation practices. We therefore used correlation analyses to clarify relationships between grain yields and the water variables after adoption of the improved practices. For example, AVYLD was correlated with SWPLNT, after improved water conservation practices were singled out in analyses of yields after 1970. The unique dependencies between MINYLD and ANPRCP ($r = 0.42$) and between MAXYLD and GSPRCP ($r = 0.42$) were also eliminated when data after 1970 were analyzed. Our data suggest that soil water conservation techniques reduced the drastic impact GSPRCP had on peak yields.

These results clearly show the importance of increased SWPLNT for achieving favorable sorghum grain yields. Increases in SWPLNT during the 1956–1997 period were achieved primarily through use of conservation tillage after 1970. This practice resulted in greater retention of crop residues on the soil surface (with no-tillage) or crop residue mulch application. Grain yield was positively correlated with GSET ($r = 0.41$ to 0.48) for the post-1970 period after conservation tillage was widely adopted for dryland crop production. The increase in grain yield with increased GSET in the absence of conservation tillage was attributed to the combined effect of GSPRCP and SWUSE, even though grain yield was not related to growing-season SWUSE. The lack of yield response to growing-season SWUSE, even though differences in SWPLNT occurred, suggests that soil water contents remained greater during the growing season when greater amounts of water were present at planting. The greater water contents often resulted from retaining larger amounts of crop residues on the surface, as with no-tillage management. These data further suggest that GSPRCP was used more effectively for grain production under such production prac-

Table 3. Correlation coefficients (r) for dryland grain sorghum production factors after improved residue management practices were typically used from 1970 to 1997, at Bushland, TX.

	r								
Factor†	AVYLD	MINYLD	MAXYLD	YEAR	ANPRCP	GSPRCP	SWPLNT	SWUSE	GSET
AVYLD	1.000	0.730***	0.926***	0.461*	0.426*	0.294	0.519**	0.060	0.385*
MINYLD		1.000	0.544**	0.203	0.467*	0.235	0.473*	0.271	0.435*
MAXYLD			1.000	0.515**	0.477*	0.387*	0.368	−0.119	0.392*
YEAR				1.000	0.233	0.160	0.354	0.058	0.235
ANPRCP					1.000	0.782***	0.070	−0.356	0.686***
GSPRCP						1.000	−0.122	−0.484**	0.868***
SWPLNT							1.000	0.492**	0.139
SWUSE								1.000	0.008
GSET									1.000

*,**,*** Significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

† AVYLD, average yield, kg ha^{-1}; MINYLD, minimum yield, kg ha^{-1}; MAXYLD, maximum yield, kg ha^{-1}; YEAR, production year; ANPRCP, annual precipitation, mm; GSPRCP, growing season rainfall, mm; SWUSE, soil water use, mm; GSET, total water use, mm.

Table 4. Parameter estimates for multiple regression of the average, minimum, and maximum grain sorghum yields (kg ha^{-1}) for the years 1956 to 1997 on production factors of year (YEAR, unitless), annual precipitation (ANPRCP, mm), soil water content at planting (SWPLNT, mm), and soil water use (SWUSE, mm). Parameter estimates are kg ha^{-1} mm^{-1}, except that the yield INTERCEPT and YEAR are in kg ha^{-1}.

	Average yield			Minimum yield			Maximum yield		
		Model R^2			Model R^2			Model R^2	
Factor	Parameter estimate	Partial	Total	Parameter estimate	Partial	Total	Parameter estimate	Partial	Total
SWPLNT	11.2 ± 3.2	0.38	0.38	6.4 ± 2.6	0.24	0.24	8.6 ± 4.5	0.05	0.05
ANPRCP	3.9 ± 1.2	0.13	0.51	4.4 ± 1.1	0.18	0.42	5.2 ± 1.7	0.11	0.16
YEAR	26.5 ± 13.7	0.05	0.56	—	—	—	55.2 ± 19.3	0.34	0.50
SWUSE	—	—	—	5.2 ± 3.3	0.03	0.45	—	—	—
INTERCEPT	−2777.8 ± 1027.1	—	—	−1932.8 ± 661.6	—	—	−3842.9 ± 1446.6	—	—

tices compared with those practices where lesser amounts of residues were present.

Multiple-Factor Effects on Grain Yield

Grain sorghum average, minimum, and maximum yields were predicted using a multiple regression model containing the more highly correlated factors. We determined both the partitioned and combined effects of the SWPLNT, ANPRCP, YEAR, and SWUSE factors on grain yield (Table 4). No single parameter consistently appeared as the most critical factor for predicting yields. However, both SWPLNT and ANPRCP appeared in all models, accounting for variations of 51% for AVYLD, 42% for MINYLD, and 16% for MAXYLD. These two factors quantify conditions that are critical to crop establishment and seasonal growth. The YEAR factor appeared in the AVYLD and MAXYLD models, but SWUSE replaced YEAR in the MINYLD model. The MINYLD conditions may reflect either limited season length or available water.

The multiple regression of AVYLD on YEAR, SWPLNT, and ANPRCP may be more revealing than regressions using the yield limits. The predicted average yield is plotted in Fig. 5 as a function of the measured average yield. Yields were predicted by a regression model that did not impose yield limits over the range of observed yields, and provided acceptable accuracy, considering the various sources of data. We identified SWPLNT as the single most important factor for increasing dryland grain sorghum yields. Favorable SWPLNT due to improved management practices govern the establishment and early growth of a grain sorghum crop. The ANPRCP, which was intercorrelated with GSPRCP and GSET, quantified the amount of water available for crop growth and subsequent grain production. Therefore, increases in ANPRCP resulted in increased yield. The yearly yield increase of about 26 kg ha^{-1} was the final component added to the regression model. Over the 40-year period of record, the average annual increase amounted to 1040 kg ha^{-1}, which is similar to the yield increase that resulted from the use of improved crop cultivars in a long-term (1958-1997) uniformly managed study.

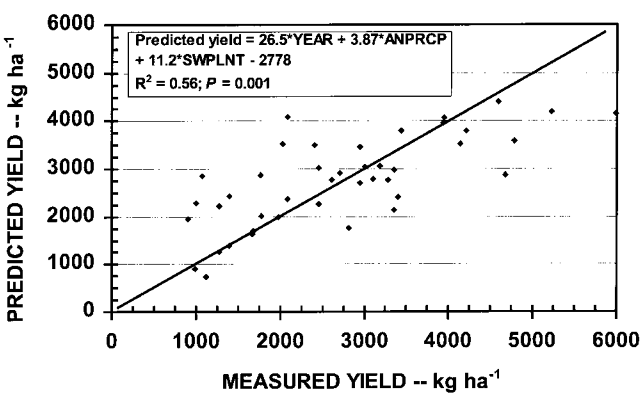

Fig. 5. Predicted average grain yield as a function of measured average yields for dryland grain sorghum in studies conducted at the USDA-ARS Conservation and Production Res. Lab., Bushland, TX (1956–1997).

Conclusions

Grain sorghum grain yields have more than tripled under research conditions at the USDA-ARS Conservation and Production Research Laboratory, Bushland, TX, from 1939 to 1997. Correlation and regression analyses were used to determine which factors were primarily related to the yield increases with time (years). We came to several conclusions from our analyses.

1. Grain yield increased steadily from 1939 to 1997 at an average of about 50 kg ha^{-1} annually during the total period of record.
2. Based on one uniformly managed 40-year study (1958–1997), introduction of improved hybrids increased yields about 46% (1020 kg ha^{-1}) during that period. An additional yield increase of 93% resulted from other factors.
3. Annual and growing-season precipitation were related to yields, but not to years of observation. Thus, the observed annual yield increases were independent of precipitation factors.
4. Growing-season evapotranspiration was related to yields, but not to year of observation; however, growing-season soil water use was not related to grain yield nor year of observation. Therefore, the observed annual grain yield increases were independent of year of observation.
5. Soil water content at sorghum planting time was the dominant factor contributing to yield increases with time. Most of the observed annual increases in soil water content at planting occurred after the early 1970s. This corresponded with the time at the Laboratory when improved herbicides became available and conservation tillage (no-tillage) re-

ceived major emphasis to retain crop residue on the soil surface.

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