

THE DEVELOPMENT AND WATER USE OF
MOISTURE-STRESSED AND NON-STRESSED
SORGHUM (SORGHUM BICOLOR (L.) MOENCH)

by

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ABSTRACT

The development, yield and water use of six sorghum (Sorghum bicolor (L.) Moench) hybrids and their respective male and female parents were evaluated under stressed and well irrigated conditions during 1980 and 1981 at Tucson, Arizona. Changes in soil moisture storage were measured by neutron modulation on a semiweekly schedule. Transpiration, diffusive resistance and leaf-ambient temperature differentials were monitored biweekly using a steady state porometer. Meteorological data was collected on a daily basis.

The 1980 season had higher maximum temperatures and pan evaporation than the 1981 season. Differences in soil moisture extraction among sorghum entries were not apparent within water treatments. Mean cumulative evapotranspiration (ET) for the stressed treatment was 270 and 261 mm, for 1980 and 1981, respectively. Mean cumulative ET for irrigated treatment was about twice that at 520 and 648 mm during 1980 and 1981, respectively. There were no apparent differences in cumulative ET for entries in the stressed treatment while genotypic differences were manifested under well irrigated conditions.

Temperature differential demonstrated a significant and negative correlation with diffusive resistance especially under stressed conditions ($r = -.64$ in 1981). Temperature differential was positively correlated with transpiration ($r = .70$ in 1980 stressed treatment).

Plant height was significantly affected by water level both years while stem weight was affected by water level only in 1980. Soil

moisture treatments did not affect leaf area either year and genotypic differences were demonstrated only in 1981.

Hybrids produced greater grain yield than their male parents under both water treatments. This was due to greater seed number for hybrids. Seed number was also more stable for hybrids under both moisture levels.

Hybrids four and seven had the greatest grain yield in 1980 and 1981, respectively. Harvest index was improved with increased water application due to increased seed number. Hybrid four in 1980 and hybrid seven in 1981 were extremely efficient in water use exhibiting ET ratios of 283 and 378, respectively under high water application. Reduced water application had little affect on the performance of these entries.

CHAPTER 1

INTRODUCTION

Nearly one-third of the Earth's land area is classified as arid or semi-arid (Paylore and Greenwell, 1979). These zones are characterized by intermittent rainfall, delivered in occasional storms of heavy intensity. The arid zones have little agriculture, except under irrigation which can guard against drought, while the semi-arid zones are populated by farmers who depend upon rainfall for agronomic survival. The semi-arid zones may receive adequate precipitation for crop production during short periods, but long dry spells of unpredictable duration are a common condition (Bailey, 1979). Crop adaptation to semi-arid zones necessitates acclimatization to drought conditions during some stage of plant growth and development (Hall, Foster and Waines, 1979). Breeding for drought resistance requires the identification of plant characteristics which permits crop production under conditions less than adequate for maximum production (Blum, 1979; Hurd, 1971; Hurd, 1976; Townley-Smith and Hurd, 1979).

Sorghum (Sorghum bicolor (L.) Moench) is an important grain crop in areas of the world which have average summer temperatures greater than 20°C and at least a 125-day frost free season. World yield in 1966 was about 56 million metric tons with an average yield of 1.09 metric tons per hectare. The United States produced about 33% and Africa produced 25% of the world total, but production in some of

the dryer African countries was only about 1/3 of the average yield per hectare (Martin, 1970). By 1979, world production had increased to 67 million metric tons. American production remained 1/3 of total production but that in Africa had decreased to 15% of the total at 9.8 million metric tons. African yields averaged 717 kg ha^{-1} compared to mean U.S. yield of 3947 kg ha^{-1} and world mean of 1322 kg ha^{-1} (Anonymous, 1980).

Although sorghum is adaptable to dryer climates, the African drought of 1969-1974 diminished crop production substantially. The region affected by this drought lies to the south of the Sahara Desert between 10° and 20°N latitude and extends the breadth of the continent (Motha and Sakamoto, 1979). Agriculture in this region, known as the Sahel, is completely dependent upon a single rainy season with a highly variable rainfall (Hall and Dancette, 1978). The millet/sorghum belt of the Sahel is bounded to the north by the 300 to 400 mm zone of annual rainfall. This zone was at least 200 km south of its "normal" position during 1973, a year considered to be one of the worst in recent decades. Due to decreased rainfall, soil moisture has diminished with the direct result of declining yields of sorghum and millet since the mid-1960's (Motha and Sakamoto, 1979).

It is imperative that mechanisms which enable sorghum and millet to produce adequate yields under limited soil moisture be isolated and characterized. These drought resistant mechanisms, if heritable, can then be incorporated into breeding programs under local conditions with indigenous sorghum and millet populations to improve varieties capable of withstanding periods of moisture stress.

This study was carried out to investigate soil moisture depletion of sorghum hybrids and their parents under conditions of limited and adequate water supply. Principal objectives were (1) to monitor soil moisture with a neutron probe, (2) to relate evapotranspiration to growth and drought resistance, and (3) identify superior germplasm with respect to drought resistance.

CHAPTER 2

LITERATURE REVIEW

Field Performance and Drought Stress

Early work by Martin (1930) demonstrated the superiority of sorghum over corn (Zea mays L.) with respect to drought. Although sorghum is recognized as a drought tolerant species, there is a vast range of varietal responses to moisture stress. Identification of genotypes with drought resistance has been the theme of many research projects. Begg and Turner (1976) regard drought resistance as the ability to grow satisfactorily in areas of periodic water deficit. This may be manifested as either avoidance or tolerance. The former involves mechanisms to maintain adequate water potential for metabolic processes while tolerance implies the ability to continue functioning at reduced water potential (Blum, 1979; Hsiao, 1973; Kramer, 1980).

Water stress has been the major limit to yield in both developed and lesser developed countries (Hanson and Nelson, 1980). Through feedback mechanisms, water stress affects other growth processes before decreased yield can be measured (Hsiao et al., 1976b). Although the conversion efficiency may not be altered (Wilson, van Bavel and McCree, 1980) and net assimilation rates may remain constant (Miyata, 1978), substrate production is reduced.

Blum (1973) analyzed the components of yield which are affected by moisture stress. Grain yield on an area basis was determined by

number of panicles per unit area and the grain weight per panicle. With decreased soil moisture, the number of panicles per unit area was the main contributor to reduced yields. This was evident by reduced tillering. Resistant entries were those with more panicles per unit area which may imply more efficient translocation.

Water use efficiency (WUE) is the ratio of dry weight produced to water consumed by evapotranspiration (Begg and Turner, 1976; Jensen, 1968). Water use efficiency can be manipulated by promoting crop competition through row arrangement (Blum and Naveh, 1976) or planting dates (Blum, 1972) when soil moisture may be limited. The choice of germplasm entries can also affect WUE. Blum (1970) and Sato (1977) showed early hybrids had greater yield in dense plantings while later maturing entries performed better when planted with wide spacings. On the other hand, if stress is sufficient to greatly reduce yields, a small supplemental irrigation may increase WUE and yield as demonstrated by Sivakumar et al. (1979).

When irrigation is available, substantial yield increases can be obtained over nonirrigation. Bielorai et al. (1964) found evapotranspiration and yield increased under irrigation. By reducing the number of irrigations, WUE was improved but at the expense of yield. Under dry conditions wider row spacings improved yield but not to the same extent as irrigation. Miyata (1978) and Sato (1977) investigated the effect of moisture stress on early and late hybrids planted at different densities. High potential evaporation, \approx 800 mm during the growing season, imposed severe stress on non-irrigated entries resulting in substantial yield reductions for both maturity classes.

Eck and Musick (1979) imposed 11 different irrigation regimes on sorghum and found the greatest yield reductions to be the result of stress at growth stages 5 to 7 according to Vanderlip and Reeves (1972). This period was also found to be the most sensitive by Lewis, Hiler and Jordan (1974). Nix and Fitzpatrick (1969) referred to this period as the "critical" time and could attribute 75% of yield reductions to a stress index. When stress was imposed around panicle initiation, floral development was delayed. After relief from stress, development continued with no yield difference between stress treatments and controls (Slatyer, 1969). There may be a period during which sorghum can go into dormancy under stressed conditions and this ability may vary with ontology.

The discovery of heterosis in sorghum has resulted in virtually 100% F_1 hybrid production in the United States (Kramer and Ross, 1970). Heterosis of hybrids over the parents has been noted for yield, height and maturity (Kambal and Webster, 1966). Blum (1977) and Gibson and Schertz (1977) attributed heterosis to faster development of the hybrid and an improved grain-filling period. Although heterosis of percentage protein in the grain was not manifested, protein per area was increased (Kambal and Webster, 1966; Liang, Overley and Casady, 1969). Jowett (1972) reported hybrids to be more stable than cultivars in east Africa. He used a method of regression analysis developed by Finlay and Wilkinson (1963) and expanded by Eberhart and Russell (1966). Jika, St. Pierre and Denis (1980) also found hybrids more stable than cultivars using a similar approach in west Africa.

Root Development and Drought Stress

Water enters the plant through the root system by Renner's "passive absorption" or water potential gradients (Kaufmann, 1976; Kramer, 1974). Differences in the root system can often explain varietal differences in ability to withstand water stress (Kramer, 1974). Depth of rooting and degree of branching can be significant with respect to water absorbing ability. Crop plants grown under semi-arid conditions will experience water deficit at some time during their growth and development. Since water can be the primary limiting factor under these conditions, root systems must supply adequate quantities if satisfactory yields are to be realized. Most of the soil moisture withdrawn by cereals is absorbed by first order laterals which can make up between 60 and 80% of the root system (Greacen, Pensana and Barley, 1976). The hair-bearing zone contributes most to absorption (Greacen et al., 1976) because little suberization has occurred in this region. Radial resistance contributes most to obstruction of water movement through plants (Weatherly, 1975; Newman, 1976; Taylor and Klepper, 1978). Once in the xylem, axial resistance is minimal in plants with extensive root systems.

Numerous researchers have compared the root system of sorghum with other crops. Early work by Miller (1916) showed corn and sorghum primary root systems were similar but sorghum had twice as many secondary roots per unit length of primary root compared to corn. Martin (1930) also found sorghum had greater secondary root growth than corn. He also reported lower osmotic potentials in sorghum roots. In more recent studies (Mayaki, Stone and Teare, 1976; Burch, Smith and Mason,

1978), investigators have shown the greater rooting density of sorghum over that of soybean (Glycine max L.).

Investigations to characterize the root system of sorghum have been undertaken. Many of these studies have dealt with only one cultivar of sorghum (Nakayama and van Bavel, 1963; Hackett, 1973; Kaigama et al., 1977). Nakayama and van Bavel (1963) used P³² and neutron modulation in a loam soil to determine root growth rates of 2 to 5 cm per day with 90% of the root activity in the upper 90 cm within 38 cm of the plant.

Intervarietal differences in aerial portions of sorghum have been compared to identify drought resistant varieties. Subterranean intervarietal differences have also been noted. Bhan, Singh and Singh (1973) found a greater number of primary and secondary roots and a higher root:shoot ratio in four drought resistant varieties as compared to four drought susceptible varieties grown in the field under natural rainfall. Blum, Arkin and Jordan (1977) used hydroponics to minimize environmental modification of rooting potential and found greater root volume in late blooming genotypes. The early blooming genotypes initiated adventitious roots sooner. Early adventitious root initiation would be beneficial in stand establishment, especially in areas of intermittent rainfall at the beginning of the season. Heterosis of sorghum hybrids over parental lines has been correlated with seminal root length, root growth rates, total length of adventitious roots and root volume (Blum, Jordan and Arkin, 1977).

Derera, Marshall and Balaam (1969) found a strong negative correlation between grain yield of wheat (Triticum aestivum L.) and

maturity when grown on stored soil moisture. This indicates drought resistance can be due to earliness. Length per unit root weight, water use efficiency and harvest index were greatest with drought resistant varieties. These parameters may be an indication of greater hydraulic resistance. Passioura (1972) has demonstrated hydraulic resistance to be significantly correlated with wheat grain yield in pot experiments. Because of reduced water use during vegetative growth, those plants with the greatest hydraulic resistance had more stored soil moisture during grain filling (Passioura, 1972).

Nour and Wiebel (1978) used sand culture to observe root characteristics. They found significant intervarietal differences with respect to drought tolerance vs. root wet weight, root volume and root:shoot ratios of 10 sorghum cultivars. Zartman and Woyewodzic (1979) suggested a genetic link between senescence and root development. Root growth and soil matric potential are closely related. Increases in soil matric potential directly affect the penetrometer soil strength (Merrill and Rawlins, 1979). Root elongation resistance is increased at elevated soil strength. Graecen and Oh (1972) have demonstrated the ability of roots to osmoregulate, thereby increasing turgor pressure to overcome the resistance. Such a mechanism would allow greater root exploration in relatively dry soils.

Bennett and Sullivan (1978) used hydroponics to study effects of adding osmoticum during panicle development on photosynthesis and root development. Both were reduced more during this stage than when stress was applied during bloom. This corresponds to the critical time reported by Nix and Fitzpatrick (1969). Jordan, Miller and Morris (1979)

studied many cultivars using hydroponics and showed considerable variation between them. They have also demonstrated remarkable plasticity and compensatory growth of sorghum roots (Jordan, McCrary and Miller, 1979). This could allow root initiation after damage during cracking of a drying soil.

Aerial Development and Drought Stress

Photosynthesis is the process by which plants make carbohydrates from solar radiation, carbon dioxide and water. The ability of a plant to photosynthesize is dependent upon the amount of CO_2 which enters through open stomates (Zelitch, 1969). Concurrently, the regulation of water loss via transpiration is controlled to a large degree by stomatal resistance (Allaway and Malthorpe, 1976; Rachke, 1976). These opposing priorities present a dilemma which has been resolved to varying degrees of success depending on environmental demand. Semi-arid crop yield is enhanced when varieties are used which can maintain photosynthesis under conditions of high evaporative demand and increased moisture stress. Shearman et al. (1972) have shown a drought resistant sorghum hybrid's ability to maintain high CO_2 uptake until it was severely stressed according to Hsiao's (1973) classification. This was due to the curvilinear nature of CO_2 uptake vs. conductance (Raschke, 1976).

Photosynthesis rates are decreased as leaf water potential is reduced. This occurs because of both stomatal closure and hampered chloroplast activity. Growth in terms of cell division and elongation

is diminished with reduced turgor (Boyer, 1976). Beadle et al. (1973) noted a rapid increase in resistance over a narrow leaf water potential range in corn. There was a less rapid and more gradual response to lowered water potential in sorghum. The increased resistance was observed at much higher water potentials than that which occurs under field conditions. McCree (1974) reasoned that differences between field and growth chamber studies were due to natural preconditioning to stress under field conditions.

Blum (1974a) suggested several positive drought response patterns. First, drought avoidance by maintaining high leaf water potential and subsequent high photosynthesis and transpiration rates. Second, high soil-leaf water potential gradients, which allow extensive utilization of soil moisture. Third, low initial moisture use prior to anthesis relative to total moisture use. He used the relationship between water saturation deficit (relative water content) and leaf water potential to measure drought or dehydration avoidance (Blum, 1974b).

Constable and Hearn (1978) observed considerable carbohydrate relocation during grain filling sufficient for dryland sorghum to out-yield irrigated soybeans. Sorghum had higher photosynthesis rates and water use efficiency (Turner et al., 1978). Photosynthesis was two to three times greater than soybeans while the transpiration rates were less. Panicle transpiration was up to 50 g H₂O/day while dark respiration had a $Q_{10} = 2.14$ between 20 and 30°C. Flag leaf photosynthesis was sufficient to maintain panicle respiration. Translocation from second and third leaves contributed the most to grain yield (Rawson, Turner and Begg, 1978). Net carbon exchange rates and conversion

efficiency are high in sorghum (Sumayao, Kanemasu and Hodges, 1977; Wilson et al., 1980) and no doubt were responsible for the greater yield of sorghum.

Henzell et al. (1975, 1976) have utilized the differences of stomatal sensitivity to screen for sorghum drought resistance but have qualified the procedure by indicating there are other mechanisms of drought resistance involved. Sorghum stomatal densities are highly heritable but have been shown to be negatively correlated with grain yield in well-watered field studies (Liang et al., 1975).

Laminar photosynthesis may be reduced in relative importance to grain yield under drought conditions. Pasternak and Wilson (1976) found that panicles contributed 12% of total photosynthate under well watered conditions but 88% of total photosynthate during stress. Transpiration was 12% of total transpiration when available soil moisture was high but only 35% of total when there was a water deficit.

Since water loss is directly related to leaf area (Liang et al., 1975; Passioura, 1976), transpirational losses may be reduced by leaf thickening while increasing photosynthesis (Delaney and Dobrenz, 1974; Nobel, Zaragoza and Smith, 1975). Transpiration is also inversely proportional to resistance (Kaufman, 1976) which should be increased with thicker leaves and/or variable internal resistance to water flow (Ackerson and Krieg, 1977). Bloom, a powdery, waxy coating on plants, can also increase resistance which in turn decreases transpiration (Chatterton et al., 1975; Hull, Wright and Bleckman, 1978).

Ebercon, Blum and Jordan (1977) have developed a method to determine epicuticular wax which may be used in large scale screening programs.

The ability of plants to increase osmotic pressure at reduced water potentials to maintain turgor is termed osmoregulation or osmotic adjustment (Hellebust, 1976; Hsiao, 1973; Hsiao et al., 1976a). Osmoregulation has been demonstrated in roots (Graecen and Oh, 1972; Martin, 1930), hypocotyls (Meyer and Boyer, 1972), growing points (Matsuda and Riazi, 1981) and leaves (Acevedo et al., 1979; Ackerson et al., 1977; Ackerson, Krieg and Sung, 1980; Fereres et al., 1978; Kassam and Elston, 1974; Jones and Turner, 1978; Stout and Simpson, 1978; Turner, Begg and Tounet, 1978). Stomatal activity is closely related with this osmotic pressure - turgor pressure interaction. Ackerson et al. (1980) were not able to similarly relate genotypes of differing stomatal sensitivity at reduced water potential with those of differing osmoregulating potential. They concluded a practical breeding program for drought resistance would have to base selections on both stomatal responses and maintenance of turgor at reduced water potential, taking into consideration the timing of stress. A more general but similar conclusion was reached by Henzell et al. (1976).

Particular metabolites have been shown to accumulate in response to water stress (Hsiao, 1973; Vaadia, 1976). Abscisic acid (ABA) increases are related to increased stomatal resistance with progressive water deficit (Beardsell and Cohen, 1975). Singh, Asperinall and Paleg (1972) suggested a correlation between stability and proline

accumulation. Blum and Ebercon (1976) related proline accumulation and post stress recovery. They thought proline may have acted as an energy reserve for respiration. Hanson (1980) on the other hand, regarded proline accumulation and drought resistance with some skepticism because proline tended to accumulate in the killed zone of severely stressed leaves. This would prevent its utilization upon relief of stress. Betaine also accumulates during stress. Betaine is an end product which is not removed upon rewatering so it may be used as an indicator of the drought stress history of plants (Hanson, 1980).

Soil - Plant - Atmosphere Continuum

The water relations of plants which includes drought induced responses must be looked at through the interdependent components of the soil - plant - atmosphere continuum. Radiant energy is the driving force of water flux from plants and soil. This flux is termed evapotranspiration and is dependent upon water potential gradients from the soil to the atmosphere with the plant as an important integrator (Jensen, 1968; Kaufmann and Hall, 1974; Kramer, 1974; Ritchie, 1974, 1980).

Evapotranspiration can be monitored by use of the water balance equation

$$ET = P + I - R - D - \Delta S$$

where ET is evapotranspiration, P is precipitation, I is irrigation, R is surface runoff, D is drainage, and ΔS is the change in soil moisture storage (Baver, Gardner and Gardner, 1972; Black, Gardner and Tanner,

1970; Hanks and Ashcroft, 1980). Precipitation and irrigation are fairly easy to measure while runoff can be held to zero in experimental plots. Methods to measure the soil moisture range from gravimetric determination through water potential measurements to neutron modulation (Rawlins, 1976). Gardner and Kirkham (1952) first demonstrated the ability to measure soil moisture with thermalized neutrons. Since then the technique has become routine in soil moisture studies. Drainage is accurately measured using lysimeters but they are expensive and time-consuming to construct in the field.

The soil can be visualized as a dynamic water container. The maximum amount which can be held is dependent upon the porosity and drainage characteristics of the soil. Veihmeyer and Hendricks (1931) termed the maximum amount of water held by a soil after drainage had ceased as "Field Capacity". This is the upper limit of moisture available under field conditions and can be approximated using 0.1 atm pressure for sandy soils (Richards, 1954). Samples can be taken 1 to 3 days after irrigation depending upon the drainage. Unfortunately, there can be considerable drainage after samples are taken so changes in soil moisture may not be simply due to plant extraction. Rose and Stern (1965) and Black et al. (1970) have used soil conductivity to approximate drainage rate with considerable success. Hillel and Benyamini (1974) used a neutron probe to compare the drainage method with an infiltration method of hydraulic conductivity determinations.

Experimentors investigating ET can assume drainage to be negligible after field capacity is determined (Turk and Hall, 1980),

or assume drainage to be the amount of water applied in excess of field capacity (Hanks, 1974). An energy approach can be used to estimate ET (Doorenbos and Pruitt, 1977; Penmann, 1948; Ritchie, 1972). The drainage component may be measured with lysimeters (Black et al., 1970; Dylla, Timmons and Shull, 1980; Ehrler and van Bavel, 1967). Evidence suggests a modified approach to field capacity would allow its use in ET investigations (Miller and Aarstad, 1971; Wilcox, 1962). McGowan (1974) and McGowan and Williams (1980a,b) have assumed drainage to cease when root activity increases in that portion of the root zone. This is indicated by a sudden increase in moisture depletion on the soil moisture-time graph as monitored with a neutron probe. If drainage is not taken into consideration in the water balance model substantial errors in estimated ET may result (Stone, Horton and Olson, 1973a,b).

There is much interest in models which predict potential evapotranspiration. The models can give an indication of potential water demand in an area or be used to schedule irrigations according to environmental considerations. Linacre (1977) developed a simple model to predict both potential ET and actual ET based upon temperature date. If more sophisticated instrumentation is available, Doorenbos and Pruitt (1977) outline procedures based on Blaney-Criddle, Makkink and Penman equations. In semi-arid, advective climates the Penman equation proves superior. Shouse, Jury and Stolzy (1980) compared several equations with results obtained by the water balance approach and found very good correlation between the Penman equation and actual

ET. Estimates based on pan evaporation were poorly correlated. Prihar et al. (1976) conversely, found pan evaporation was a good method to schedule irrigation.

Water balance and root distributions can be determined using a neutron probe. Holbrook and Welsh (1980) found no significant difference in root depth and distribution of short and tall winter wheat. Both types were able to extract deep soil moisture under dryland conditions. Singh and Russell (1979) followed the profile moisture loss on an alfisol, a major soil type in the semi-arid tropics. Stone et al. (1976) found that extraction patterns of soil moisture loss were about the same during the early season but water depletion was about 15 cm below root growth during the later period of growth. This may suggest water movement into the root zone from lower depths.

CHAPTER 3

MATERIALS AND METHODS

A field experiment was carried out during the summers of 1980 and 1981 at the USDA Plant Material Center, Tucson, Arizona. The soil was a Comoro loamy sand (coarse-loamy, mixed, calcareous, thermic Typic Torrifuvent) (Gelderman, 1972). Four grain sorghum hybrids and their respective female and male parents were planted in a Randomized Complete Block design with three blocks. Planting at a rate of 13 seed m^{-1} was undertaken on 14 May, 1980 and 12 May, 1981 with two cone planters set for 50 cm between rows. Two levels of water application were established, stressed and fully irrigated, and 12 sorghum entries were included within each water treatment. Entries were planted in 5-row plots, 7.6 m in length (19.35 m^2).

The sorghum material was experimental germplasm donated by DeKalb Seed Co., Lubbock, Texas. The entries were unregistered and still under development so designated simply as F1, M1, H1 through F4, M4 and H4 in 1980 and F5, M5, H5 through F8, M8 and H8 in 1981. The F, M and H refer to female parent, male parent and hybrid, respectively. Six entries were used during both seasons. Entries F1, M1, H1, F4, M4 and H4 from 1980 were renumbered in 1981 as F5, M5, H5, F8, M8 and H8, respectively. The renumbered material was of the same germplasm during both seasons.

Plots were thinned between growth stage 1 and 2 to 15 cm between plants resulting in a uniform population of 250 plants per plot. This density was equivalent to approximately 129,000 plants ha⁻¹. Atrazine (2-chloro-4-(ethylamino)-6-isopropylamino-s-triazine) was used for weed control (Heathman, 1972). It was applied at rates of 0.90 kg ha⁻¹ active ingredient 22 days after planting (DAP) in 1980 and 0.67 kg ha⁻¹ active ingredient, 30 DAP in 1981. Commercial ammonium phosphate (16-20-0) was applied at a rate of 50 kg N ha⁻¹, 34 DAP in 1980. In 1981, ammonium sulfate (21-0-0), superphosphate (0-45-0) and Sul-Po-Mag (0-0-20) were applied 10 April equivalent to 202 kg N ha⁻¹, 83 kg P ha⁻¹, 210 kg N ha⁻¹, 140 kg Mg ha⁻¹ and 512 kg S ha⁻¹.

Plastic, class-160 PVC tubes, 5 cm in diameter by 150 cm in length were installed between rows in the center of each plot 21 DAP in 1980 and 1981. These access tubes were used for neutron moderation to monitor soil moisture fluctuations throughout the season. A Campbell Pacific Model 503 neutron probe was used semiweekly during 1980 and 1981 to obtain 30-s counts at 15, 45, 75 and 105 cm depths. Counts at each depth were divided by the mean of 20 standard counts obtained at the beginning and half way through each day's measuring period. The resulting count ratios were entered into equations developed for the instrument. Moisture content at each measured depth was used to represent moisture distribution in the soil profile to 120 cm in 30-cm increments. Soil samples were taken at four sites to determine bulk density and moisture content at 0.1, 10 and 15 bars using a pressure plate apparatus. Table 1 presents the mean water content at

Table 1. Bulk density, volumetric moisture content and equivalent water depth of soil profile for Comoro loamy sand.

Soil Profile Increment (cm)	Bulk Density (g/cm ³)	Moisture Content					
		0.1 Bar		15.0 Bar		Available	
		Vol. (%)	Depth (mm)	Vol. (%)	Depth (mm)	Vol. (%)	Depth (mm)
0-30	1.38	17.21	50	6.60	20	10.61	30
30-60	1.34	18.63	55	6.89	20	11.74	35
60-90	.29	25.49	75	7.30	22	18.19	55
90-120	1.29	34.17	102	7.83	23	26.34	79

0.1 and 15 bars. Available moisture was determined as the difference between these values. Mean volumetric available moisture in the profile was 16.72% and ranged from 10.61 to 26.34%.

The neutron probe was field calibrated 54 days after an irrigation to develop a volumetric percent moisture vs. count ratio standard curve (Nakayama and Reginato, 1982). An access tube similar to those used in the study had been installed in a fallow area next to a water-stressed plot. Means of five 30-s standard counts and five 30-s counts taken at 15, 45, 75 and 105 cm were used to determine the count ratios for each depth. Replicated soil samples were taken 2 to 3 cm from the access tube in 4.0 cm increments to a depth of 120 cm. Weighed means were used to determine volumetric moisture content at the measured center of influence of the neutron probe source. Figure 1 represents the regression of volumetric moisture content on count ratio for the probe used in 1980 and 1981. The R^2 values are greater than 0.99 and although the equations are very similar, respective equations were used each year for determinations.

The water stressed treatment was imposed by terminating irrigation 13 DAP in 1980 and 30 DAP in 1981. No attempt was made to prohibit rain from the site. Irrigated plots were watered throughout the season when available moisture was reduced to 50% of maximum. Water was pumped from a subsurface irrigation line to each main plot and distributed evenly through gated pipe arranged perpendicular to rows. Flow rate was maintained at $57 \text{ m}^3 \text{ hr}^{-1}$ for a period sufficient to deliver 10 or 15 cm irrigations.

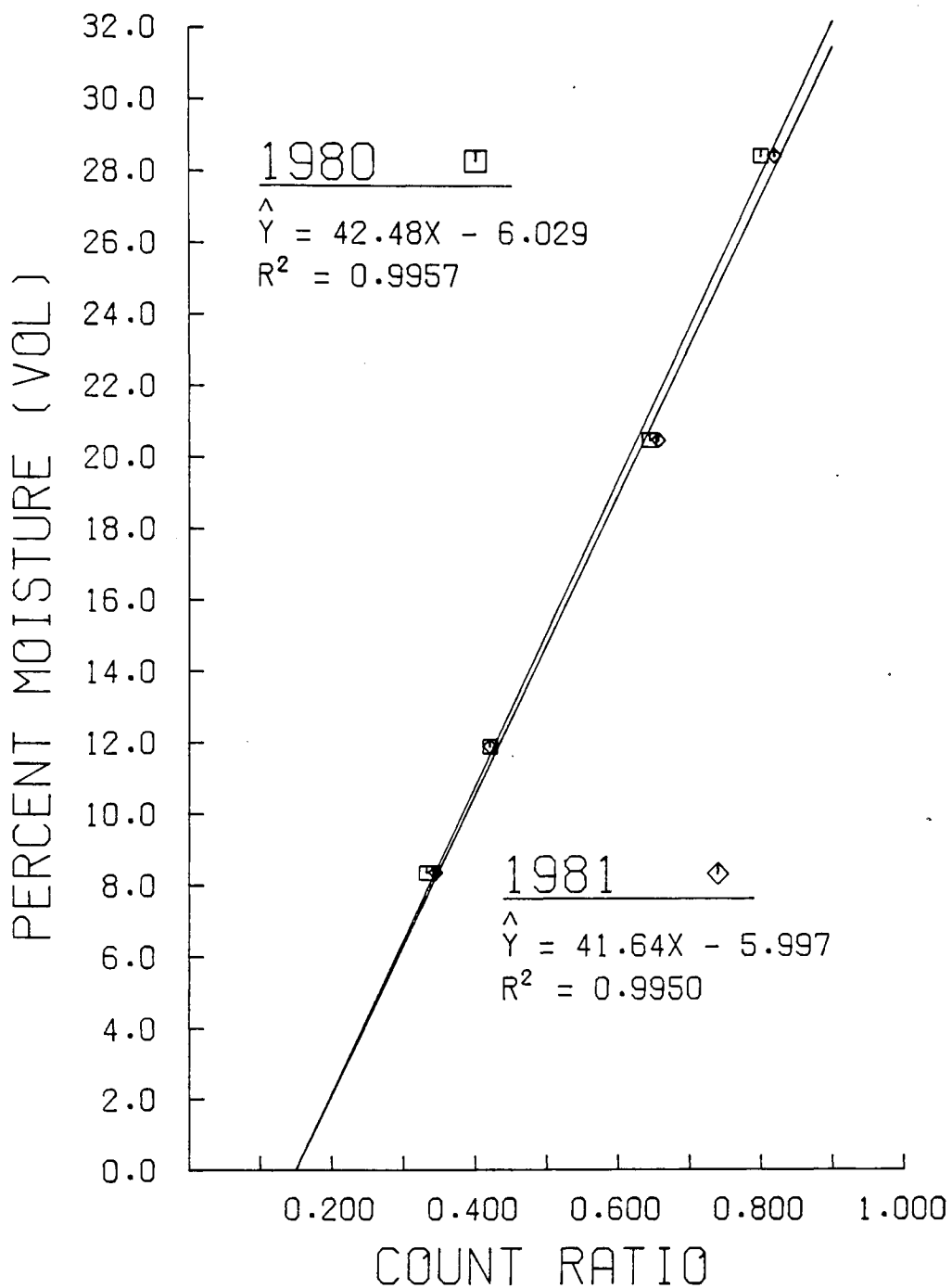


Figure 1. Calibration curves used for Campbell Pacific neutron probe in Comoro loamy sand during 1980 and 1981.

Evapotranspiration (ET) was calculated using the water balance method. Precipitation, irrigation and storage changes were measured, runoff was prevented and water in excess of 280 mm was assumed to be drainage. Calculated ET between measurement dates were summed through 99 DAP in 1980 and 105 DAP in 1981.

A Li-Cor LI-1600 steady state porometer was used biweekly to measure afternoon leaf and ambient temperatures ($^{\circ}\text{C}$), diffusive resistance (s cm^{-1}) and transpiration ($\mu\text{g cm}^{-2} \text{s}^{-1}$). The adaxial surface of the uppermost, fully expanded leaf was used for the measurements.

Severe bird pressure necessitated bagging of panicles to insure grain yield estimates. Twenty main heads in each plot were covered with selfing bags shortly after anthesis. Grain developing on uncovered panicles was completely destroyed by birds. Attempts with chemical repellents in adjacent plots and passive scaring techniques in experimental plots proved fruitless.

Bagged heads of hybrids and male parents were harvested 4 Oct., 143 DAP in 1980. Male sterile, female parents were disregarded. In addition, two plants from each plot were harvested and separated into leaves, stems and seedless panicles. This material was dried for two days at 70°C and the mean weight of two plants was determined. Mean total leaf area of two plants for each entry was measured with a Hayashi Denko leaf area meter for estimates of specific leaf weight (SLW). Grain from bagged heads of each plot was threshed and bulked. Total weight was divided by head number and adjusted to 5% moisture to determine grain yield per plant. Three hundred seed weight was

determined and adjusted to 1,000 seed weight at 5% moisture. Similar procedures were followed in 1981 although leaves, stems and grainless panicles were harvested 92 DAP and grain harvest was 135 DAP.

Maximum and minimum temperatures as well as precipitation were collected at the Plant Material Center weather station, 0.5 km from the experiment site. Pan evaporation was determined by the Hydrology Department, University of Arizona at a station 1.5 km from the field. Pan evaporation was compared to calculated evaporation developed by Linacre (1977). His formula was a simplified version of the Penman formula and needed only temperature, elevation and latitude as inputs. The equation used was:

$$E_o = \frac{700 T_m / (100-A) + 15(T-T_d)}{(80-T)}$$

where E_o is open evaporation, $T_m = T + 0.006h$, T is the mean temperature and h is the elevation (696.5 m at the Plant Material Center). The latitude, A , was 32.267°N at the site. The dew point was expressed as T_d but the relationship $(T-T_d)$ was determined by the equation:

$$0.0023h + 0.37T + 0.53R + 0.35R_{\text{ann}} - 10.9^\circ\text{C}$$

where R is the mean daily range of temperature and R_{ann} is the difference between the mean temperatures of the hottest and coldest months (18.5°C at PMC).

Analysis of data was conducted as a split plot with two water levels as main plots and 12 entries as sub-plots. The Statistical Packages for the Social Sciences (SPSS) were used in a Cyber 175

computer. Figures were drawn with a Calcomp plotter at the University Computer Center.

CHAPTER 4

RESULTS AND DISCUSSION

Meteorological Parameters

Mean daily temperature was nearly 20°C at the time of planting in 1980 (Fig. 2). A cooling period one week after planting lasted for a few days. Temperatures thereafter remained high. There were 60 days with maximum temperatures equal to or in excess of 40°C during the 99-day growth period. Mean maximum temperature during June and July (18 to 78 DAP) was 39°C. Minimum daily temperature reached 20°C, 44 DAP and remained near that point for the rest of the period. High temperature and little rainfall (only 118 mm) coupled to impose severe evaporative demand. Pan evaporation was 1325 mm, averaging greater than 13 mm day⁻¹. This was approximately equivalent to 0.26 m³H₂O plot⁻¹ day⁻¹ or 260 kg H₂O plot⁻¹ day⁻¹. Calculated evaporation according to the Linacre (1977) method totalled 1218 mm or roughly 12.3 mm day⁻¹.

Mean daily temperatures during 1981 (Fig. 3) were similar to those of 1980 (Fig. 2). The 1981 temperature range was not as great as during 1980 with only 24 days which had maximum temperatures equal to or greater than 40°C. Mean maximum temperature during June (20 to 49 DAP) was 39°C and during July (50 to 80 DAP) was 37°C. Substantial precipitation during July contributed to lower maximum temperatures while cloud cover prevented minimum temperatures from declining to the

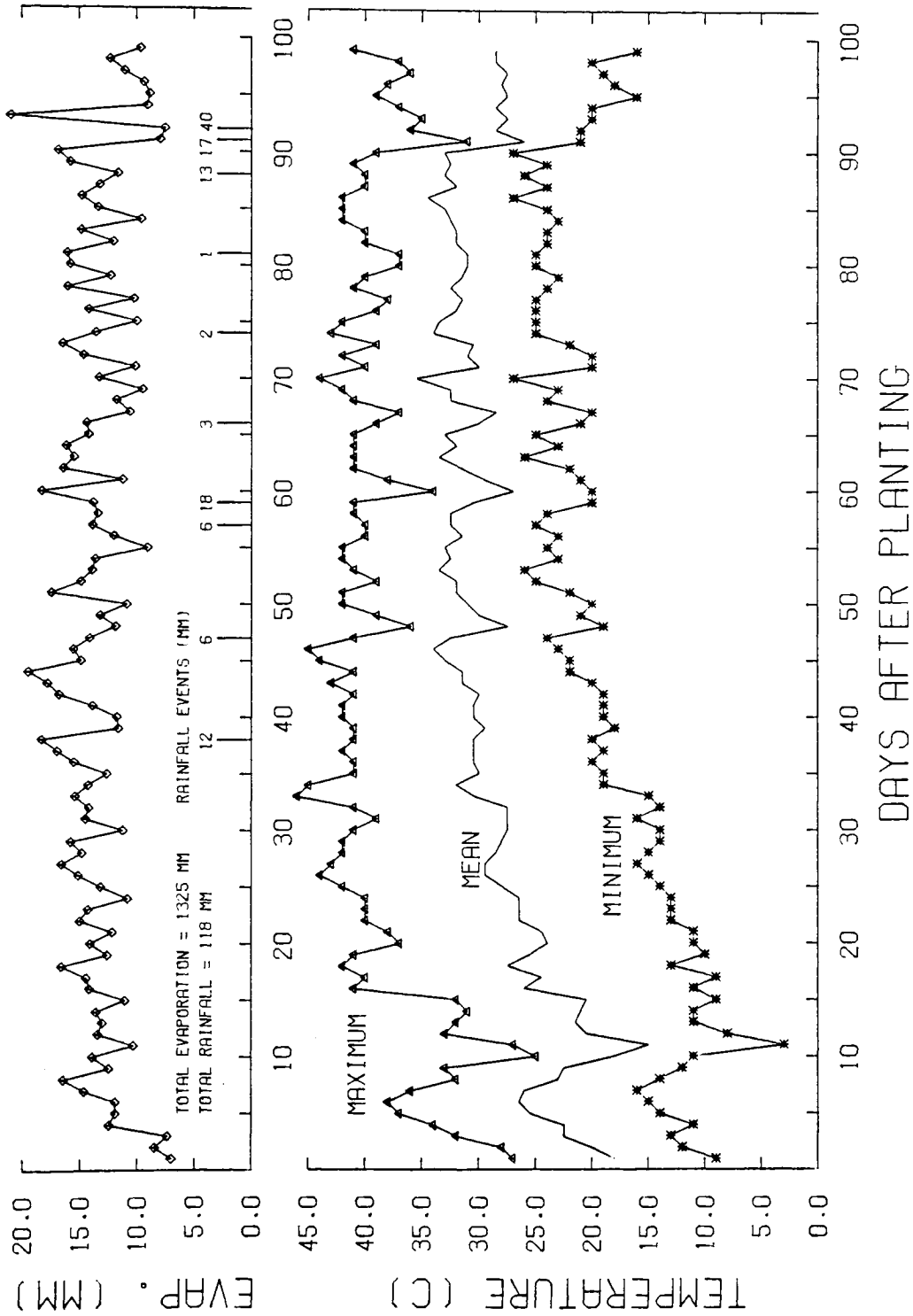


Figure 2. Meteorological data at the USDA Plant Material Center, Tucson, Arizona after the 14 May, 1980 planting.

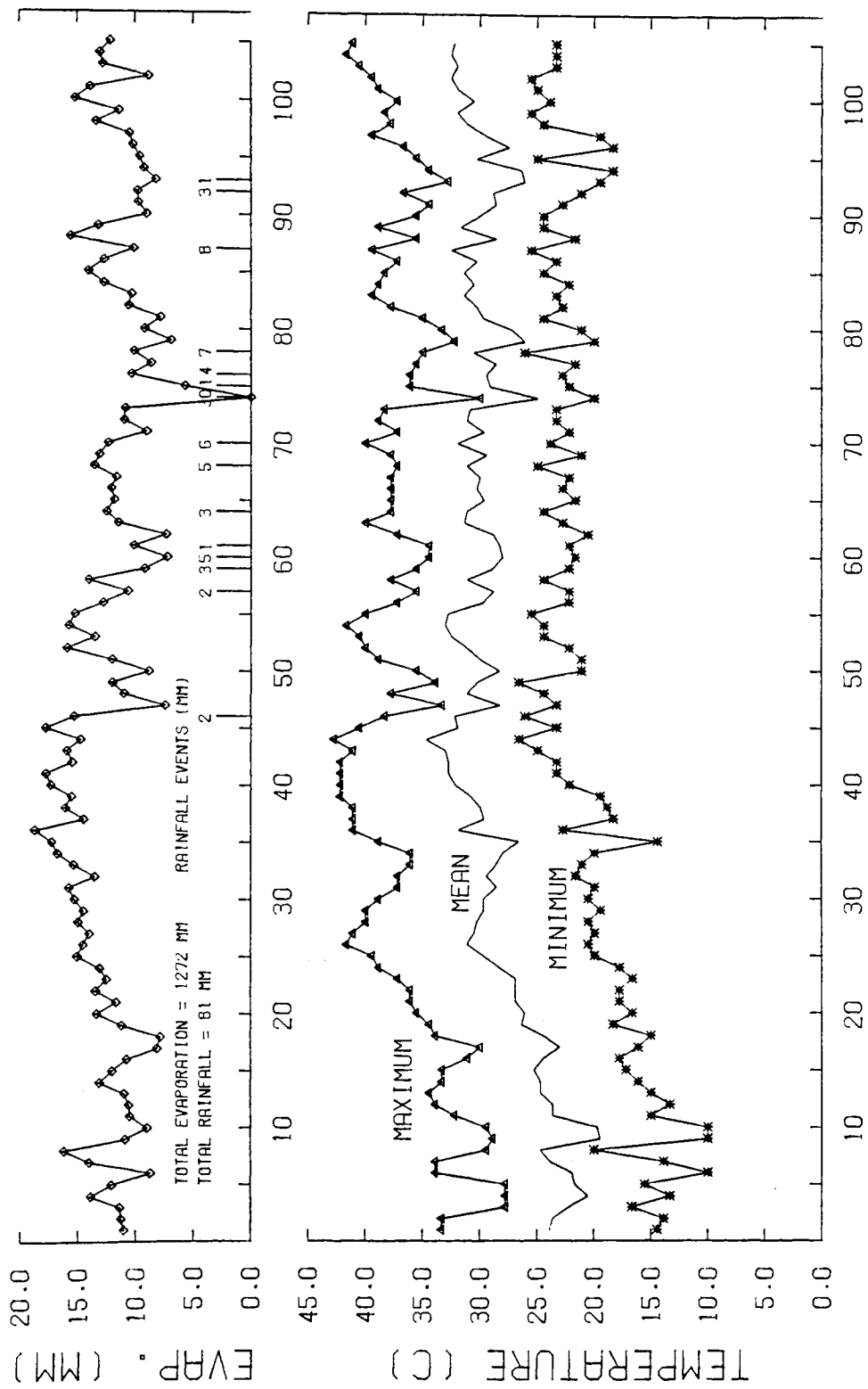


Figure 3. Meteorological data at the USDA Plant Material Center, Tucson, Arizona after the 12 May, 1981 planting.

same extent as 1980. Evaporation was consequently reduced during 1981, totaling 1272 mm through 105 DAP (1196 mm through 99 DAP compared to 1325 mm during 1980). This still resulted in an evaporation rate greater than 12 mm day^{-1} for the period ($230 \text{ kg H}_2\text{O plot}^{-1} \text{ day}^{-1}$). Total calculated evaporation was 1210 mm or 11.5 mm day^{-1} , less than 5% different from measured evaporation.

Soil Moisture Depletion

Analysis of variance for each date showed very little difference in soil moisture extraction among sorghum entries at each depth within a treatment. The mean of all entries was therefore used to develop soil moisture depletion patterns. The soil moisture profile for the stress treatment in 1980 is shown in Figure 4. Mean standard deviation of moisture depth ranged from 11.4 mm in the first 30-cm to 20.9 mm in the last 30-cm increment. Water holding capacity increased with depth (Table 1), ranging from 30 to 79 mm. Moisture was reduced to 35 mm (50% of available moisture) 42 DAP in the upper 30-cm depth. Available moisture at that time was reduced to 50% at 50, 54 and 64 DAP in the second, third and fourth 30-cm increments, respectively. Available moisture, in the first 30-cm increment, reached 0% at 58 DAP. Precipitation shortly after increased soil moisture to nearly 50% in this portion of the profile but was not sufficient to penetrate into the second 30-cm increment. Rapid depletion in the upper profile after rain indicated roots were able to exploit increased soil moisture. Precipitation on 88, 91 and 92 DAP (59% of total) penetrated to 90 cm.

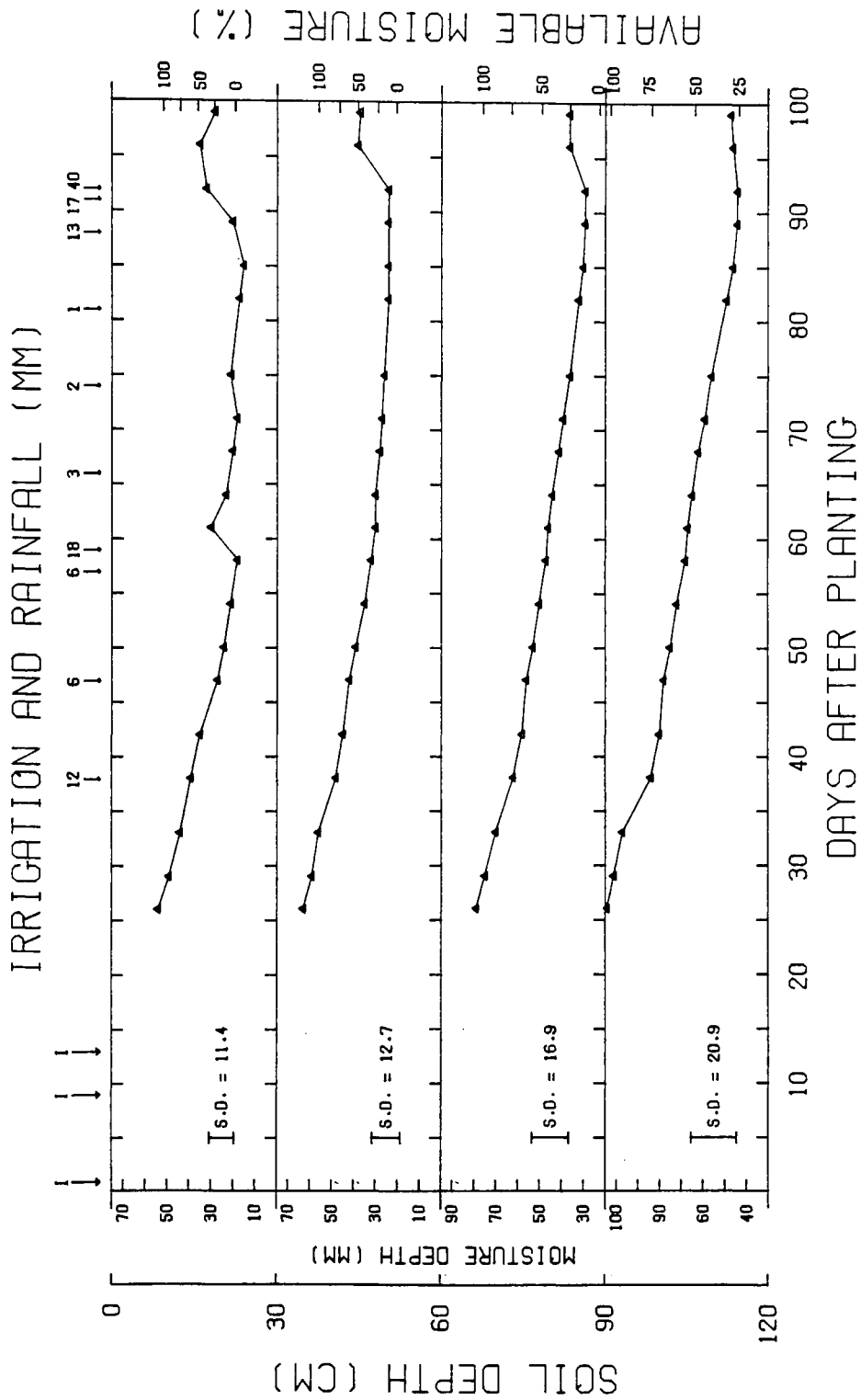


Figure 4. Soil moisture profile at four depths for stressed treatment after the 14 May, 1980 planting. Large arrows (I) indicate irrigation, small arrows indicate rainfall.

Soil moisture was increased to 50, 50 and 25% of available moisture in the upper three 30-cm increments, respectively.

The mean soil moisture standard deviations ranged from 9.8 to 16.2 mm under irrigated conditions during 1980 (Fig. 5). Soil moisture was approaching 0% in the first increment and 50% in the second increment when irrigated at 55 DAP. Further irrigations at 65, 72, 79 and 86 DAP maintained soil moisture at approximately 50, 75, 75 and 75% of available moisture in the 30, 60, 90 and 120-cm depths, respectively for the remainder of the period.

Mean standard deviations for soil moisture in stressed treatment in 1981 were very similar to those of 1980, ranging from 9.8 to 20.2 mm (Fig. 6). Soil moisture in the upper two 30-cm increments was depleted to 50% available moisture earlier in 1981, although there were six irrigation in 1981 vs. three in 1980 prior to stress imposition. Available moisture was 50% at 38 and 48 DAP at 30 and 60-cm depths, respectively, as opposed to 42 and 50 DAP at similar depths in 1980. Cumulative pan evaporation at 38 DAP was 511 mm in 1980 and 494 mm in 1981. Fifty percent available moisture which was reached 4 days later in 1981 than 1980 at the 90-cm depth, was similar during both seasons with 50% of the available moisture being depleted 64 DAP. Heavy precipitation in July, 1981 (83% of total) caused a higher soil moisture for the remainder of the season in the stressed treatment than during the same period in the 1980 stressed treatment.

Soil moisture during the growth period at various depths in the profile for the 1981 irrigated treatment is presented in Figure 7.

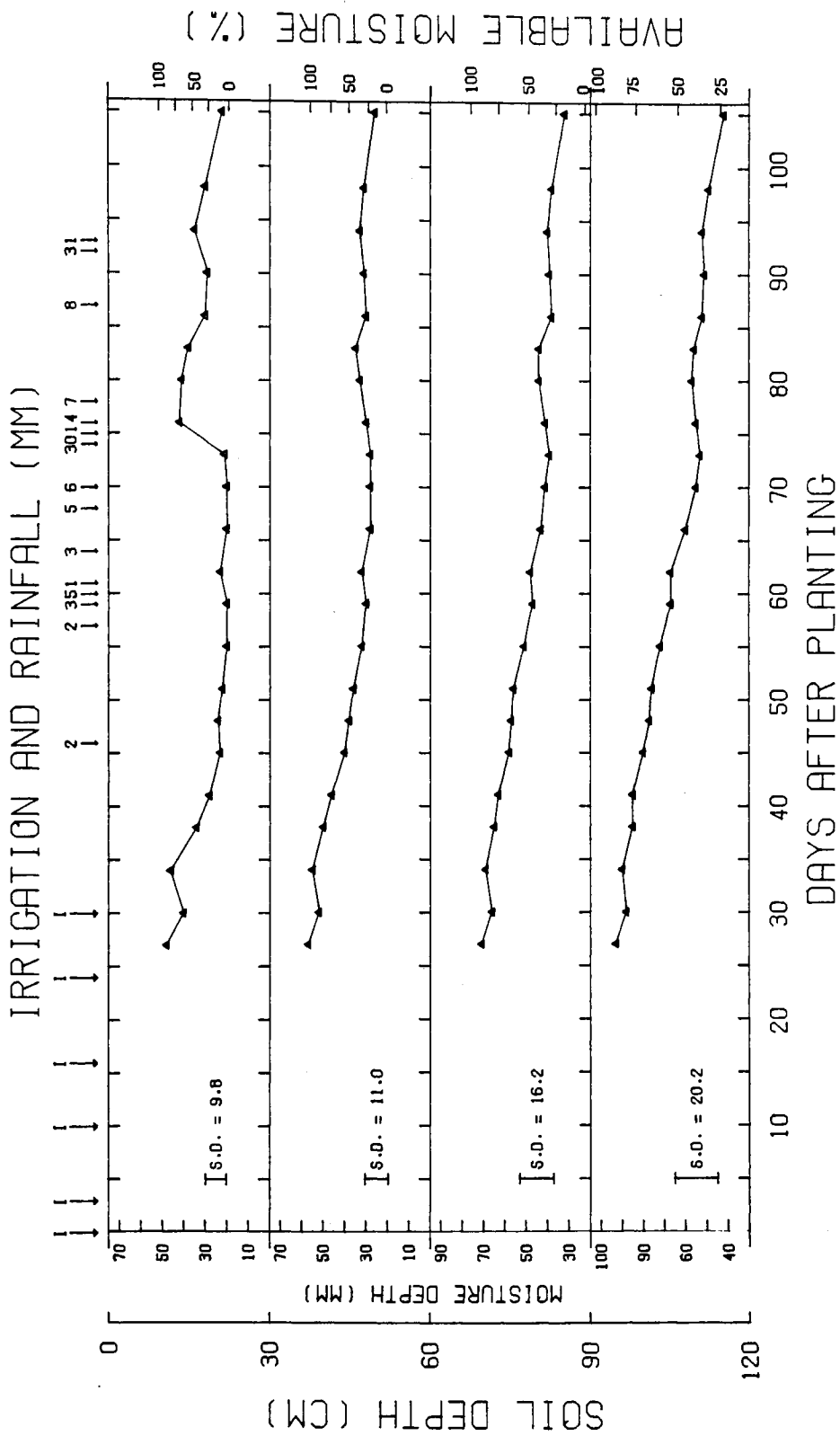


Figure 6. Soil moisture profile at four depths for stressed treatment after the 12 May, 1981 planting. Large arrows (I) indicate irrigation, small arrows indicate rainfall.

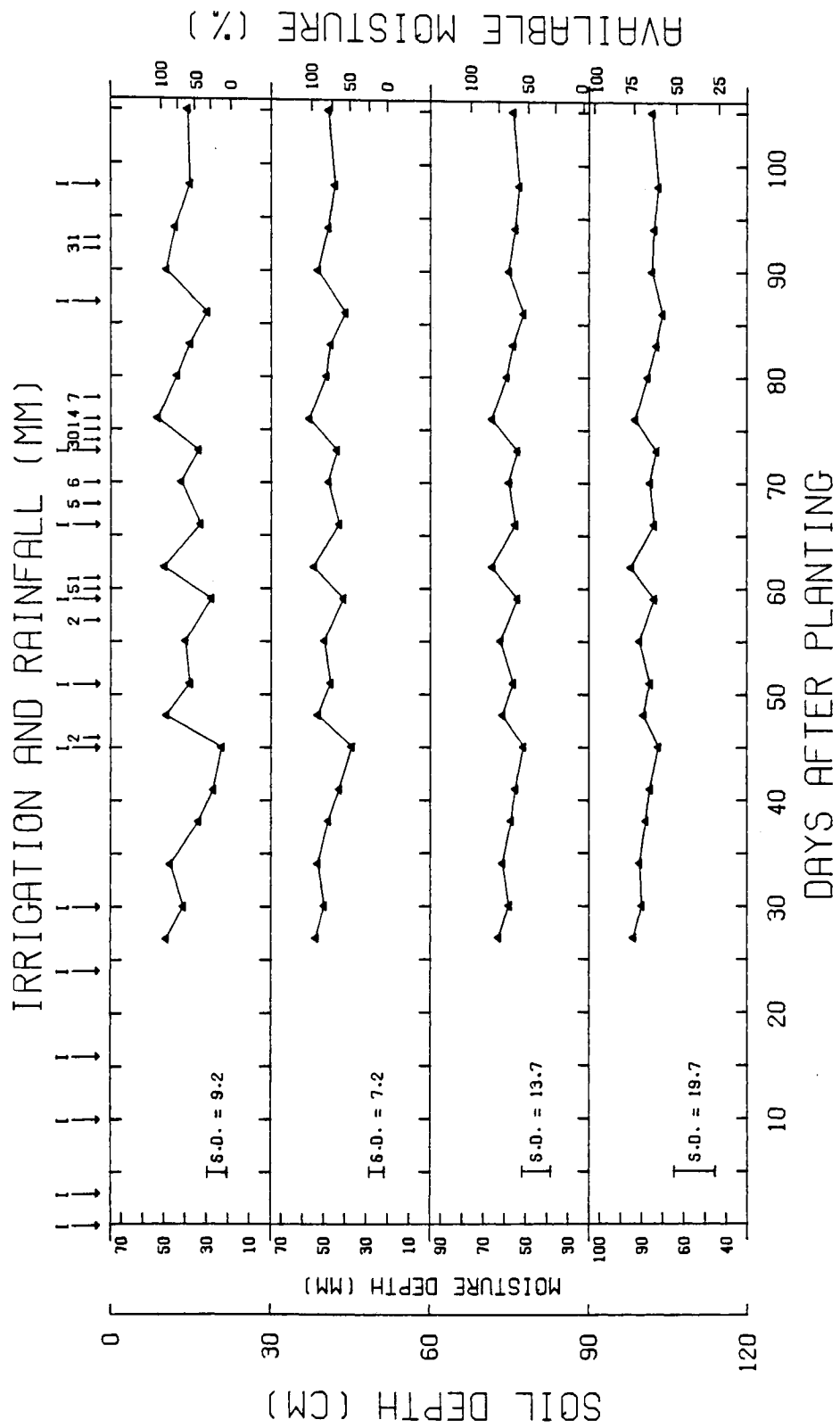


Figure 7. Soil moisture profile at four depths for irrigated treatment after the 12 May, 1981 planting. Large arrows (I) indicate irrigation, small arrows indicate rainfall.

There were more irrigations in 1981 than 1980; 13 vs. 8, totaling 1476 mm and 1168 mm in 1981 and 1980, respectively. Individual irrigations in 1980 were generally 50 mm greater than irrigations in 1981. Less water was applied per irrigation in 1981; therefore, the 90 and 120-cm depth averaged 5% less available moisture after 60 DAP than the same depths during 1980. Mean soil moisture standard deviation was similar to irrigated treatments in 1980. Soil moisture was depleted to 50% in the first 30-cm increment as under stressed conditions (38 DAP) and in the 60-cm depth at 50 DAP. Water applications thereafter were sufficient to maintain soil moisture above 50% in all but the upper 30-cm of the soil profile.

Evapotranspiration

Changes in soil moisture (mm), as measured with the neutron probe were used in the water balance equation to determine evapotranspiration (ET). Cumulative evapotranspiration, calculated from 25 through 99 DAP was very similar for all sorghum entries under stressed conditions during 1980 (Fig. 8). Total moisture lost through ET in the stressed treatment ranged from 243 mm for Hybrid 2 (H2) to 296 mm for H4. Pan evaporation during this same period was 994 mm. Severe soil moisture stress (Fig. 4) limited ET to an average of 27% of pan evaporation.

Mean cumulative ET for the irrigated treatment was twice that of the stressed treatment, averaging 52% of pan evaporation. Hybrids two and four had total ET greater than their respective parents. Male

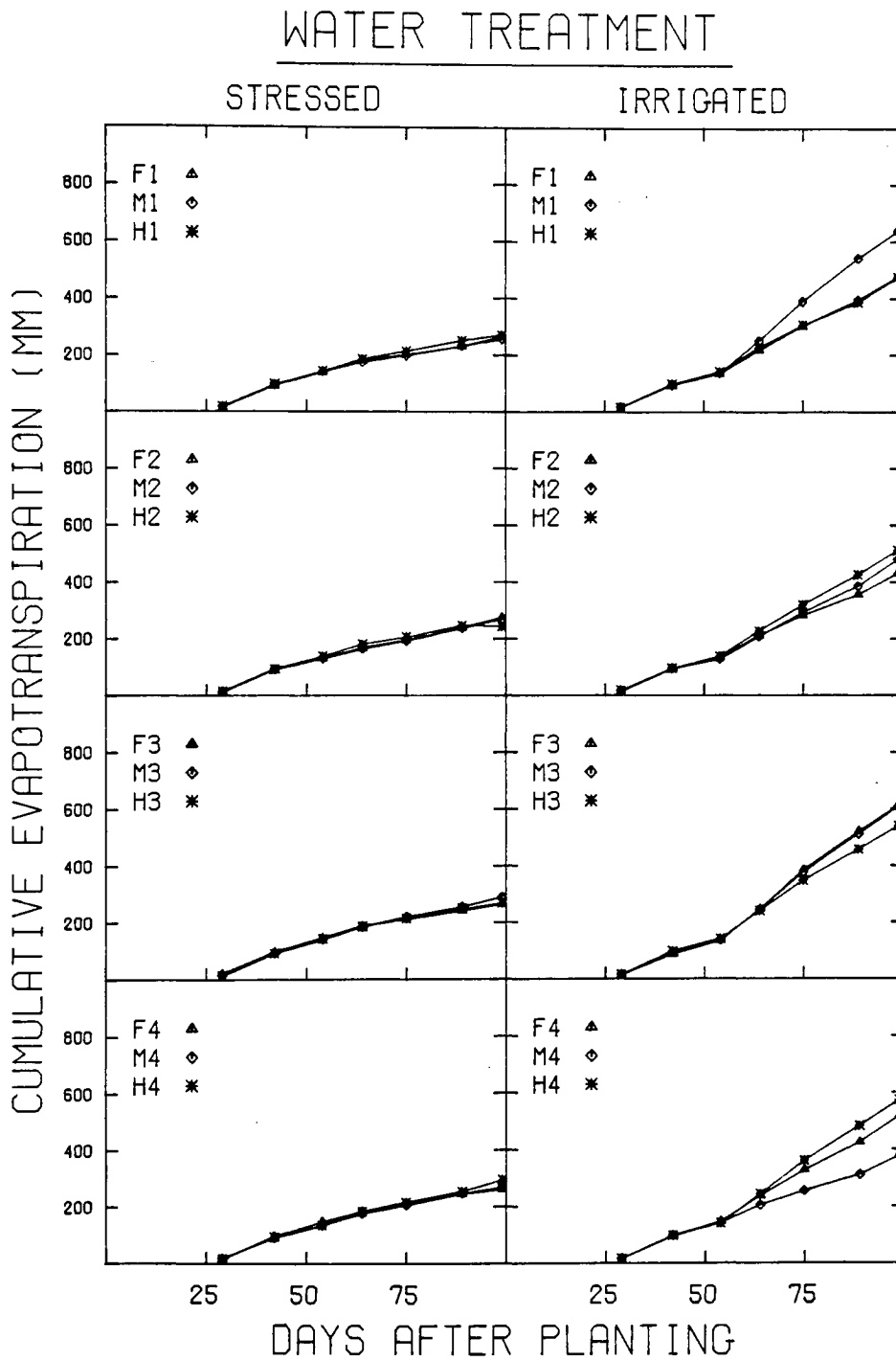


Figure 8. Cumulative evapotranspiration for 12 sorghum entries under stressed and irrigated treatments after the 14 May, 1980 planting.

one lost the greatest amount of water, 638 mm, while male four removed the least at 378 mm.

Pan evaporation from 23 through 105 DAP in 1981 amounted to 951 mm, somewhat less than 1980. Entries in the stressed treatment during 1981 (Fig. 9) responded similarly to entries under the same conditions in 1980; mean cumulative ET was 261 mm or 27% of pan evaporation.

Under irrigated conditions, M5 (M1 in 1980) reversed itself in 1981 by exhibiting the least cumulative ET at 355 mm (Fig. 9). This appeared due to inordinately small moisture changes in the upper profile. Hybrid eight (H4 in 1980) again had a cumulative ET greater than either of its parents and lost the largest amount of water for all 1981 entries at 795 mm. Hybrid five also removed more water than its parents while H6 and H7 removed less than their parents. Mean cumulative ET was greater in 1981 than 1980 resulting in 68% of pan evaporation being lost through evapotranspiration.

Hofmann (1982), working with the same germplasm, found mean diffusive resistance ($s\ cm^{-1}$) over both treatments to be greater in 1980. Hybrid four removed 574 mm of water through ET (Fig. 8) under irrigation in 1980 while exhibiting the greatest mean seasonal transpiration rate, $26.0\ \mu g\ cm^{-2}\ s^{-1}$ (Hofmann, 1982). The same germplasm, H8, transpired at the highest rate in 1981 under both moisture regimes and maintained a high leaf to ambient temperature differential (Hofmann, 1982).

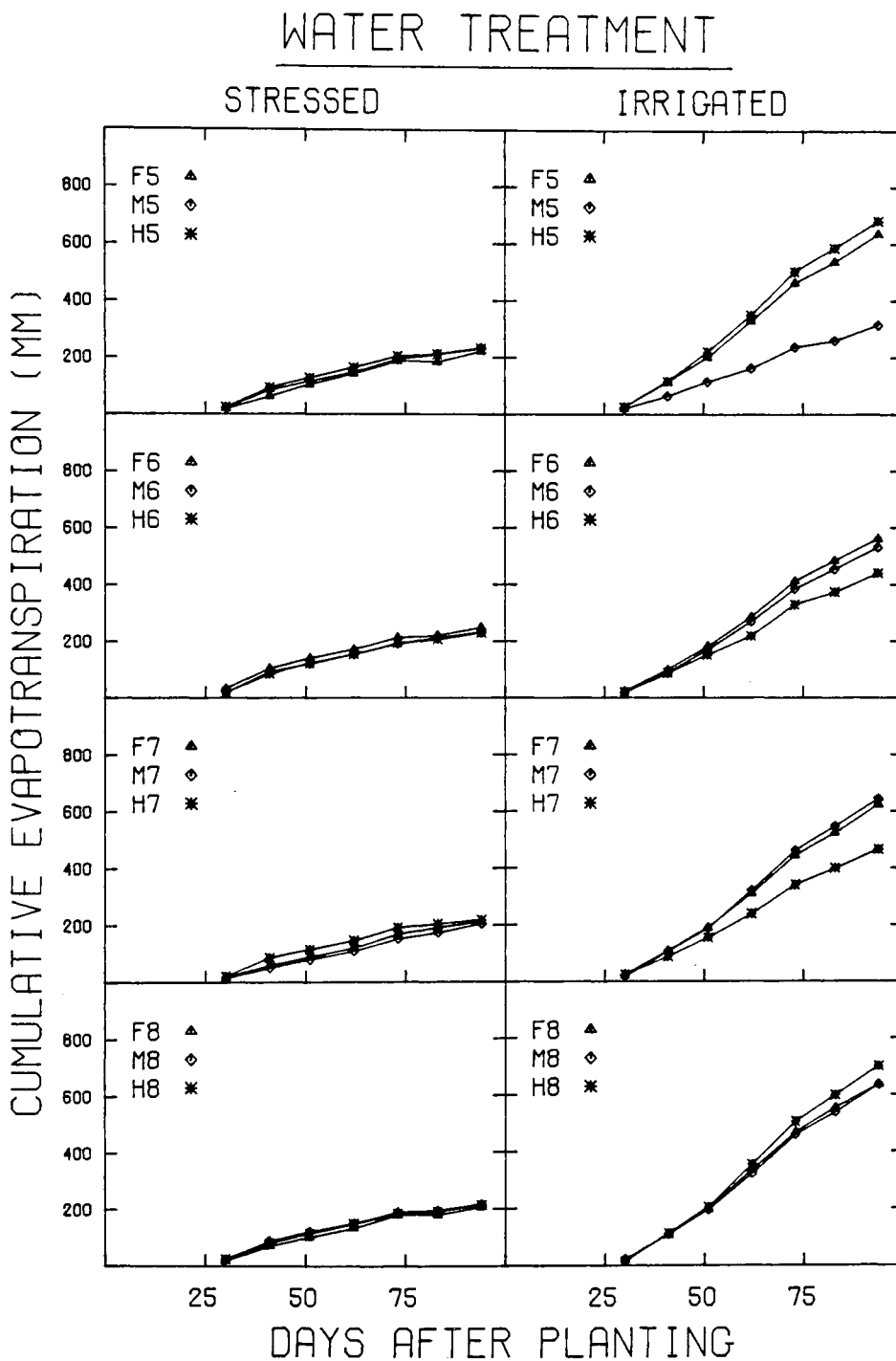


Figure 9. Cumulative evapotranspiration for 12 sorghum entries under stressed and irrigated treatments after the 12 May, 1981 planting.

Various physiological parameters measured with the Li-Cor LI-1600 porometer were correlated. All parameters demonstrated highly significant correlations (Tables 2, 3). Leaf to ambient temperature differential ($^{\circ}\text{C}$) was inversely related to diffusive resistance (s cm^{-1}) and directly related to transpiration ($\text{ug cm}^{-2} \text{s}^{-1}$). Higher correlations between temperature differential and resistance were obtained each season in stressed treatments. Temperature differential and transpiration were not as highly correlated in 1981 as 1980 in the stressed treatment. This may have resulted from less stress in 1981 due to heavy precipitation during July (Fig. 3) and higher soil moisture (Fig. 6). Temperature differentials may be a good indication of water status (Ehrler et al., 1978) or transpiration rate (Mtui, Kanemasu and Wasson, 1981). Log transformations of resistance and transpiration improved their correlation because of the curvilinear nature of their relationship. The transformed values were more negatively related in both treatments during 1980 than 1981. Mean transpiration was greater in 1980, the same year that diffusive resistance was greater (Hofmann, 1982) indicating other variables may have a significant influence on this relationship.

Growth and Yield

All hybrids, except H2, developed faster than their male parents in 1980 under both irrigation treatments. Days to growth stage four (Vanderlip and Reeves, 1972) ranged from 71 to 85 (Table 4). Water level had no effect on days to boot stage although soil moisture was severely limited at that time in the stressed treatment

Table 2. Pearson correlation coefficients for various LI-1600 porometer parameters and transformations for 12 sorghum entries grown under stressed and irrigated conditions during 1980.

	Δ Temperature Stressed Irrigated	Resistance Stressed Irrigated	Log Resistance Stressed Irrigated	Transpiration Stressed Irrigated	Log Transpiration Stressed Irrigated
Δ Temperature Stressed Irrigated	-	-	-	-	-
Resistance Stressed Irrigated	-.49**	-	-	-	-
Log Resistance Stressed Irrigated	-.70**	.82**	.78**	-	-
Transpiration Stressed Irrigated	.70**	-.55**	-.87**	-.85**	-
Log Transpiration Stressed Irrigated	.68**	-.83**	-.97**	.90**	.94**

**Significance at the $p < 0.001$ level.

Table 3. Pearson correlation coefficients for various LI-1600 porometer parameters and transformations for 12 sorghum entries grown under stressed and irrigated conditions during 1981.

	$\frac{\Delta \text{ Temperature}}{\text{Stressed}}$	$\frac{\text{Irrigated}}$	$\frac{\text{Resistance}}{\text{Stressed}}$	$\frac{\text{Irrigated}}$	$\frac{\text{Log Resistance}}{\text{Stressed}}$	$\frac{\text{Irrigated}}$	$\frac{\text{Transpiration}}{\text{Stressed}}$	$\frac{\text{Irrigated}}$	$\frac{\text{Log Transpiration}}{\text{Stressed}}$	$\frac{\text{Irrigated}}$
$\frac{\Delta \text{ Temperature}}{\text{Stressed}}$	-	-								
$\frac{\text{Irrigated}}$										
$\frac{\text{Resistance}}{\text{Stressed}}$	-.64**		-							
$\frac{\text{Irrigated}}$										
$\frac{\text{Irrigated}}$	-.40**									
$\frac{\text{Log Resistance}}{\text{Stressed}}$	-.59**		.96**		-					
$\frac{\text{Irrigated}}$										
$\frac{\text{Irrigated}}$	-.48**		.84**							
$\frac{\text{Transpiration}}{\text{Stressed}}$	.54**		-.71**		-.70**		-			
$\frac{\text{Irrigated}}$										
$\frac{\text{Irrigated}}$	.64**		-.54**		-.72**		-			
$\frac{\text{Log Transpiration}}{\text{Stressed}}$	.53**		-.77**		-.73**		.98**			
$\frac{\text{Irrigated}}$										
$\frac{\text{Irrigated}}$	.57**		-.67**		-.77**		.96**			

**Significance at the p < 0.001 level.

Table 4. Number of days from planting to growth stage four for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Boot (Days After Planting)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
H3	71 a ⁺	F3	71 a	H6	61 a	H6	58 a
H4	72 a	F4	72 ab	F5	64 a	F5	61 ab
F3	72 a	H4	72 ab	F6	64 ab	H5	62 ab
F4	72 a	H3	73 ab	F8	65 ab	F6	62 ab
F1	72 a	F1	73 abc	H8	65 ab	M5	64 abc
H1	76 ab	H1	73 abc	H5	67 ab	M6	64 abc
H2	76 ab	H2	74 abc	M6	71 bc	F8	65 abc
M3	80 bc	M4	78 bcd	H7	74 c	H8	65 abc
M2	82 bc	M3	79 cd	M5	75 c	H7	68 bcd
M1	82 c	M1	80 d	M7	75 c	F7	70 cde
M4	85 c	M2	81 d	F7	76 c	M7	73 de
F2	85 c	F2	83 d	M8	77 c	M8	75 e
Mean	77 ± 5.7		76 ± 4.7		70 ± 6.6		66 ± 5.4

⁺ Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

(Fig. 4). Genotypic differences were also evident in 1981 under both moisture regimes. Hybrid 7 and its respective parents were later in development than all other hybrids. There was a greater numeric difference, although not significant, between stressed and irrigated treatments in 1981 with stressed treatment being somewhat delayed. Boot stage occurred one week earlier in 1981, which was undoubtedly due to more precipitation and lower maximum temperatures (Fig. 3). Vanderlip (1972) and Vanderlip and Reeves (1972) reported panicle initiation to be about 20 days before boot. Panicle initiation during the more stressful year (1980) may have been delayed because of higher evaporation rates at that sensitive stage (Begg and Turner, 1976; Slatyer, 1969).

Anthesis dates (Vanderlip and Reeves, 1972) were in the same general order as boot but occurred one week later (Table 5). Hybrids developed at a rate more similar to their female parent although usually more rapid. Treatment effects were not evident either year. The 1980 sorghum entries bloomed 65 to 85 DAP under high water application using a line source irrigation system in Yuma, Arizona during 1981 (Marcarian et al., 1981, unpublished data). Female parents, being male sterile, did not set pollen. Hybrids and male parents were bagged shortly after anthesis to prevent bird damage.

Plant height (Table 6) was significantly affected by water treatment. Mean height was 13 and 7 cm less in stressed treatment during 1980 and 1981, respectively. There was very little difference between sorghum parents and hybrids in the stressed treatment and no

Table 5. Number of days from planting to growth stage five for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Anthesis (Days After Planting)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
H3	77 a ⁺	F4	78 a	H6	68 a	H6	65 a
H4	78 a	H3	79 a	F5	71 ab	H5	69 ab
F1	79 a	F3	79 ab	F6	72 ab	F6	70 ab
F4	79 a	H4	79 ab	H8	72 ab	M6	71 ab
F3	80 a	F1	80 ab	F8	73 ab	M5	71 ab
H1	82 ab	H2	81 ab	H5	74 ab	F5	72 ab
H2	82 ab	H1	81 ab	M6	76 bc	F8	72 ab
M2	86 bc	M3	86 bc	H7	81 cd	H8	72 ab
M3	87 bc	M4	87 c	M7	82 cd	H7	75 bc
M1	89 c	M1	87 c	M5	82 cd	F7	77 bcd
F2	90 c	M2	88 c	F7	83 d	M7	80 cd
M4	91 c	F2	90 c	M8	85 d	M8	82 d
Mean	83 ± 5.3		83 ± 4.9		77 ± 6.7		73 ± 5.3

⁺Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

Table 6. Height to flag leaf collar for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Height (cm)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed		Irrigated		Stressed		Irrigated	
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
M2	45 a ⁺	F4	58 N.S. [#]	F6	36 a	F6	42 a
M1	46 a	F1	59	H6	49 b	F5	54 b
F4	48 ab	M1	60	F8	50 b	F8	57 bc
F2	48 ab	M2	61	F5	50 b	H6	60 bcd
F1	49 ab	M4	63	M5	51 b	M5	63 cd
M4	49 ab	F2	64	M6	53 b	M6	63 cd
M3	52 ab	H3	64	H5	56 bc	H8	63 cd
H2	52 ab	H4	65	M8	59 cd	H5	65 d
H1	53 ab	F3	67	H8	61 cd	M8	66 d
F3	54 ab	M3	67	F7	65 de	F7	72 e
H4	54 ab	H1	68	M7	67 e	M7	79 f
H3	57 b	H2	68	H7	75 f	H7	82 f
Mean	51* ± 5.7		64* ± 4.2		56* ± 10.3		63* ± 10.9

⁺ Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

[#] N.S. Means are not significantly different at the 5% level according to the SNK method.

* Treatments are significantly different at the 5% level according to the SNK method.

difference in the irrigated treatment during 1980. Hybrids were generally, although not significantly, taller than their parents. There was a greater genotypic range of height in 1981. Hybrid six was the only hybrid shorter than its male parent. All other hybrids were taller than their respective parents and male parents were generally taller than female parents.

Panicles from two unbagged plants within each plot were weighed each season. The material did not include grain because of bird damage. There were no significant differences between genotypes within any treatment or between treatments either year (Table 7). Greater tillering in 1980 resulted in more dry matter per plant and therefore greater panicle weights. Hybrid four in 1980 and H8 in 1981 had numerically the largest panicles in the stressed treatment.

Stem weight (Table 8) was significantly affected by water application only in 1980. Genotypic variability was evident in the irrigated treatment in 1981 with H7 and F7 exhibiting the greatest stem weight. These entries were also the tallest in 1981 along with M7 in the irrigated treatment (Table 6). Female six was the shortest entry in 1981 and had stem weights not significantly different from F5, the entry with the smallest stem weight under irrigated conditions.

Leaf weights (Table 9) were similar to stem weight in lack of significant differences between entries in both treatments in 1980 and in the stressed treatment in 1981. Significant differences in the 1981 irrigated treatment were minimal with F7 having the greatest leaf weight. Soil moisture treatments had no affect on leaf weight either

Table 7. Weight of seedless panicles for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Panicle Weight (g)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed		Irrigated		Stressed		Irrigated	
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
H2	14.8 N.S. ⁺	M3	11.5 N.S.	H5	5.1 N.S.	H7	5.2 N.S.
H3	15.0	F3	14.3	H7	5.6	F5	5.2
M2	16.0	F1	15.5	F5	5.7	M5	5.4
M3	17.0	H3	15.5	H6	5.7	F8	5.4
M1	17.5	M2	16.3	M7	6.0	H5	6.7
F1	18.5	F4	16.8	F8	6.2	M6	6.8
H1	18.5	H2	17.8	M5	6.4	M7	7.0
F4	19.3	M1	18.0	F7	7.2	H6	7.4
F3	19.8	H4	20.0	F6	7.3	F6	8.4
F2	20.8	H1	21.5	M6	7.4	H8	8.9
M4	25.3	M4	25.3	M8	7.9	M8	9.3
H4	34.8	F2	25.8	H8	8.1	F7	9.7
Mean	19.8 ± 7.3		18.1 ± 4.9		6.5 ± 2.3		7.1 ± 2.5

⁺N.S. Means are not significantly different at the 5% level according to the SNK method.

Table 8. Weight of stems for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Stem Weight (g)									
1980					1981				
Water Treatment					Water Treatment				
Stressed		Irrigated			Stressed		Irrigated		
Entry	Mean	Entry	Mean		Entry	Mean	Entry	Mean	
H2	43.3 N.S. ⁺	F1	52.7 N.S.		M7	19.4 N.S.	F5	19.1 a [#]	
F1	49.0	M3	56.5		F5	19.6	F8	21.1 ab	
H3	50.8	H2	57.0		F6	21.9	F6	21.8 ab	
M2	56.5	F3	58.5		F8	22.3	M8	27.3 abc	
M3	61.3	F4	65.3		M5	25.7	H6	28.6 abc	
F4	63.5	H4	65.8		H6	25.8	F7	35.6 abcd	
M1	70.8	M2	69.8		M6	26.5	M6	40.5 bcd	
F3	71.0	H3	70.8		M8	28.9	H8	40.7 bcd	
H4	76.0	M4	80.3		H5	32.1	H5	42.8 cd	
F2	83.0	M1	87.3		H8	33.2	M5	43.4 cd	
M4	83.5	H1	88.8		H7	33.7	H7	50.1 d	
H1	84.8	F2	99.0		F7	34.4	M7	51.2 d	
Mean	66.1* <u>+19.8</u>		70.9* <u>+18.2</u>			27.0 <u>+9.3</u>		35.2 <u>+13.9</u>	

⁺N.S. Means are not significantly different at the 5% level according to the SNK method.

[#]Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

*Treatments are significantly different at the 5% level according to the SNK method.

Table 9. Weight of leaves for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Leaf Weight (g)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated	Stressed	Irrigated
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
H2	15.0 N.S. ⁺	H2	17.3 N.S.	F5	10.0 N.S.	F5	8.5 a [#]
M3	18.3	H4	17.3	H6	10.5	F8	8.9 ab
M2	18.8	H3	18.3	M7	11.0	F6	10.7 ab
M1	19.0	F1	20.0	F8	11.4	H6	11.2 ab
H3	19.3	M3	20.3	F6	11.7	H8	13.1 ab
F1	20.0	M1	20.5	M6	13.7	M6	13.7 ab
F4	23.8	F3	21.3	H5	13.8	H7	14.5 ab
H1	24.3	F4	22.0	M5	14.0	M5	15.0 ab
H4	25.8	M2	22.5	F7	14.7	H5	15.1 ab
F3	26.3	H1	24.0	H7	15.0	M8	15.7 ab
F2	28.0	M4	25.8	H8	16.3	M7	16.4 ab
M4	28.8	F2	28.3	M8	17.4	F7	17.1 b
Mean	22.3+6.5		21.5+4.5		13.3+3.8		13.3+3.7

⁺ N.S. Means are not significantly different at the 5% level according to the SNK method.

[#] Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

year. Leaf weight was greater in 1980 due to increased tiller numbers. The plant material was harvested later in 1980 than 1981 (143 vs. 92 DAP, respectively), after secondary stem elongation.

Total leaf area of two plants from each entry was used to determine specific leaf weight (SLW). Mean SLW for each entry by year is presented in Table 10. Values were very similar each year with means of 6.53 and 5.94 mg cm⁻² for 1980 and 1981, respectively.

Total leaf area per plant (Table 11) was determined by dividing leaf weight (Table 9) by SLW (Table 10) and multiplying by 10 to convert into dm². Water treatment had no effect on leaf area either year as other environmental (Acevedo et al., 1979) and physiological (Matsuda and Riazi, 1981) parameters influence leaf growth. There were no genotypic differences in 1980 but some differences among hybrids and parents did occur in 1981. Female two, which had the largest numerical leaf area in 1980 had the smallest transpiration rate under both treatments (Hofmann, 1982). This resulted in a cumulative ET of 276 and 432 mm in stressed and irrigated treatments, respectively (Fig. 8). These rates were about average in the stressed treatment and less than average in the irrigated treatment. Hybrid 8, which had equal leaf areas under both regimes (Table 11), lost 795 vs. 250 mm under irrigated and stressed conditions (Fig. 9) due to substantially different mean seasonal transpiration rates under each moisture regime (Hofmann, 1982).

Significant differences of mean panicle grain yield were evident each year under both water treatments (Table 12). Hybrids

Table 10. Specific leaf weight for 12 sorghum entries grown during 1980 and 1981.

Entry	Specific Leaf Weight (mg/cm ²)						
	1980				1981		
	SLW	Entry	SLW	Entry	SLW	Entry	SLW
F1	6.44	F3	6.37	F5	5.69	F7	5.44
M1	6.19	M3	5.94	M5	6.42	M7	5.91
H1	6.75	H3	6.19	H5	6.13	H7	5.70
F2	6.61	F4	6.44	F6	6.36	F8	5.63
M2	6.94	M4	7.61	M6	4.57	M8	5.93
H2	6.13	H4	6.78	H6	6.98	H8	6.54

Table 11. Leaf area for 12 sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Leaf Area (dm ²)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed		Irrigated		Stressed		Irrigated	
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
H2	24.5 N.S. ⁺	H4	25.4 N.S.	H6	15.1 a [#]	F5	15.0 a
M2	27.0	H2	28.1	F5	17.7 ab	F8	15.8 ab
M3	30.7	H3	30.3	F6	18.4 ab	H6	16.0 ab
M1	30.7	F1	31.1	M7	18.6 ab	F6	16.8 ab
H3	31.1	M2	32.4	F8	20.3 ab	H8	20.1 ab
F1	31.1	M1	33.1	M5	21.7 ab	M5	23.4 ab
H1	35.9	F3	33.4	H5	22.5 ab	H8	24.7 abc
F4	36.9	M4	33.8	H8	24.9 ab	H7	25.5 abc
M4	37.8	M3	34.1	H7	26.2 ab	M8	26.4 abc
H4	38.0	F4	34.2	F7	26.9 ab	M7	27.8 abc
F3	41.2	H1	35.6	M8	29.4 ab	M6	29.9 bc
F2	42.4	F2	42.7	M6	30.1 b	F7	31.4 c
Mean	33.9 _± 9.1		32.6 _± 6.3		22.7 _± 7.2		22.7 _± 7.1

⁺N.S. Means are not significantly different at the 5% level according to the SNK method.

[#]Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

consistently outyielded their male parents although in some instances this difference was not always significant. Hybrid four had the greatest yield in 1980 and H8 (same germplasm) was not significantly different than H7, the highest yielder in 1981. Water treatment had no significant effect on yield although the irrigated treatment was numerically greater than the stressed treatment each year.

Weight of 1,000 seed (Table 13) was unaffected by water treatment. Male four had the greatest 1,000 seed weight, irrespective to soil moisture in 1980. Only H1 in 1980 had a larger seed weight than its male parent under stressed conditions. In the 1980 irrigated treatment, H2, H3 and H4 all had significantly smaller seed size than their male parents. Hybrid five in 1981 (H1 in 1980) again had larger seeds than its male parent in the stressed treatment. The 1,000 seed weight of other hybrids was statistically equal to or less than their respective male parents. Under irrigated conditions in 1981, all hybrids had 1,000 seed weights which were not significantly different than their male parents. The 1,000 seed weight reported are similar to those determined in various sample sizes by Ross and Kofoed (1978).

Various agronomic and water-use parameters were calculated from previous tables and are presented in Table 14 for 1980 and Table 15 for 1981. Seed per head was calculated by dividing yield (Table 12) by 1,000 seed weight (Table 13) times 1,000 for each hybrid and its male parent. Hybrids consistently had greater seed numbers per head than their respective parents under each moisture treatment in 1980 and 1981. Heterosis of sorghum hybrids over parents has been

Table 12. Grain yield adjusted to 5% moisture for eight sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

Yield/Head (g)							
1980				1981			
Water Treatment		Water Treatment		Water Treatment		Water Treatment	
Stressed		Irrigated		Stressed		Irrigated	
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
M3	13.4 a ⁺	M3	15.2 a	M5	15.2 a	M6	23.3 a
M1	15.6 a	M1	32.4 a	M6	16.0 ab	M7	27.9 ab
M2	17.9 a	M2	35.8 ab	M7	21.7 abc	M5	29.3 ab
M4	30.2 b	H3	36.9 ab	H5	23.0 abc	M8	30.9 ab
H3	33.6 b	M4	41.6 ab	H6	24.6 bc	H8	31.2 ab
H2	39.1 bc	H1	43.3 ab	M8	26.5 c	H5	35.5 b
H1	45.1 c	H2	45.8 bc	H8	30.0 c	H6	36.8 b
H4	46.6 c	H4	53.5 c	H7	30.9 c	H7	37.1 b
Mean	30.2+14.2		38.0+11.4		23.8+6.5		31.5+5.9

⁺Means followed by the same letter within a treatment are not significantly at the 5% level according to the SNK method.

Table 13. Weight of 1,000 seed adjusted to 5% moisture for eight sorghum entries grown under stressed and irrigated conditions during 1980 and 1981.

1,000 Seed Weight (g)							
1980				1981			
Water Treatment				Water Treatment			
Stressed		Irrigated		Stressed		Irrigated	
Entry	Mean	Entry	Mean	Entry	Mean	Entry	Mean
M1	17.7 a ⁺	H1	18.4 a	M5	13.2 a	M5	14.4 a
H1	20.0 b	M1	18.7 a	M6	16.3 b	H5	15.4 ab
H2	23.3 c	H2	21.5 b	M7	16.8 b	M7	17.4 bc
H3	23.8 c	H3	22.6 bc	H5	17.1 b	H6	18.1 bcd
M2	25.0 c	M2	24.3 c	H7	17.4 b	M6	18.8 cd
H4	25.7 c	H4	25.3 c	H6	18.6 b	H7	18.8 cd
M3	28.0 d	M3	27.9 d	H8	19.2 b	H8	19.7 cd
M4	31.9 e	M4	30.7 e	M8	23.4 c	M8	20.8 d
Mean	24.4 _± 4.4		23.7 _± 4.4		17.8 _± 3.0		17.9 _± 2.3

⁺ Means followed by the same letter within a treatment are not significantly different at the 5% level according to the SNK method.

Table 14. Calculated agronomic parameters based on yield and water use for 12 sorghum entries grown under stressed and irrigated conditions during 1980.

Entry	Water Treatment											
	Stressed						Irrigated					
	Seed per Head	Total Plant Weight (g)	Harvest Index	ET per Plot (kg)	ET Ratio	Entry	Seed per Head	Total Plant Weight (g)	Harvest Index	ET per Plot (kg)	ET Ratio	
F1	-	88	-	5147	234	F1	-	88	-	9249	420	
M1	881	123	0.13	4973	162	M1	1733	158	0.20	12345	313	
H1	2250	173	0.26	5263	122	H1	2353	178	0.24	9191	207	
F2	-	132	-	5341	162	F2	-	153	-	8359	219	
M2	716	109	0.16	5205	191	M2	1473	144	0.25	9288	258	
H2	1678	112	0.35	4702	168	H2	2130	138	0.33	9907	287	
F3	-	117	-	5147	176	F3	-	94	-	11842	504	
M3	479	112	0.12	5631	201	M3	545	104	0.15	11745	452	
H3	1412	119	0.28	5205	175	H3	1564	142	0.26	10468	295	
F4	-	107	-	5070	190	F4	-	104	-	10004	385	
M4	947	168	0.18	5225	124	M4	1355	173	0.24	7314	169	
H4	1813	183	0.25	5728	125	H4	2115	157	0.34	11107	283	

Table 15. Calculated agronomic parameters based on yield and water use for 12 sorghum entries grown under stressed and irrigated conditions during 1981.

	Water Treatment											
	Stressed						Irrigated					
	Entry	Seed per Head	Total Plant Weight (g)	Harvest Index	ET per Plot (kg)	ET Ratio	Entry	Seed per Head	Total Plant Weight (g)	Harvest Index	ET per Plot (kg)	ET Ratio
F5	-	35	-	5012	573	F5	-	33	-	13855	1679	
M5	1152	61	0.25	5341	350	M5	2035	93	0.31	6869	295	
H5	1345	74	0.31	5205	281	H5	2305	100	0.35	14861	594	
F6	-	41	-	5553	542	F6	-	41	-	12461	1216	
M6	984	64	0.25	5166	323	M6	1239	84	0.28	11533	549	
H6	1337	67	0.37	5089	304	H6	2033	84	0.44	9849	469	
F7	-	56	-	4818	344	F7	-	62	-	13584	876	
M7	1292	58	0.31	4838	334	M7	1603	103	0.27	14145	549	
H7	1776	85	0.36	5186	244	H7	1973	107	0.35	10101	378	
F8	-	40	-	4586	459	F8	-	35	-	13874	1586	
M8	1132	81	0.33	5050	249	M8	1486	83	0.37	13951	672	
H8	1563	88	0.34	4838	220	H8	1560	94	0.33	15383	655	

attributed to greater seed number per head (Kambal and Webster, 1966). Increased yield of male parents under irrigated conditions was due to substantial increase in seed numbers as stress has been shown to affect primordia (Slatyer, 1969). Hybrids maintained more stable seed number under both water treatments. Hybrid four which had the greatest yield in 1980 also had the highest 1,000 seed weight rather than larger seed numbers. Hybrid seven, which had the greatest yield under both moisture levels in 1981 (Table 12), had smaller seed size than H8 (Table 13) but greater seed numbers. Blum (1973) has shown drought resistant hybrids to be those with high seed numbers under stressed conditions. Both H2 and H3 had more seeds per head than H4 in the irrigated treatment.

Total plant weight (Tables 14, 15) was the sum of panicle (Table 7), stem (Table 8), leaf (Table 9) and grain (Table 12) weights. Hybrids were generally larger than either parent. Female two was larger than H2 because of considerable stem size under irrigated and stressed conditions in 1980. Differences in total plant weight between years was due to more prolific tillering in 1980.

Harvest Index (Tables 14, 15) was determined by dividing grain yield (Table 12) by total plant weight. Hybrid eight under irrigated conditions was the only hybrid which had a harvest index less than its male parent. Hybrid six, a relatively small entry with limited leaf area, had the largest harvest index under each moisture level in 1981. High harvest index under stressed conditions was a good indicator of drought resistance (Derera et al., 1969). In 1980, H1 demonstrated

substantial stability in seed numbers and harvest index with differential irrigation. The same germplasm, renumbered as H5, had reduced seed numbers in the stressed treatment in 1981 but a stable harvest index. Hybrid eight (H4 in 1980) exhibited the greatest stability over irrigation treatments and years for seed numbers and harvest index.

Evapotranspiration per plot (Tables 14, 15) was determined by multiplying the total cumulative ET from 25 to 99 DAP in 1980 (Fig. 8) and 23 through 105 DAP in 1981 (Fig. 9) by plot area for each entry. Mean ET was 2.2 times greater in irrigated plots over both seasons. Female five, with the smallest leaf area in the 1981 irrigated treatment (Table 11), consumed more water than F7 with twice the leaf area. Mean transpiration rate of F5 was also greater than F7 (Hofmann, 1982).

The ET ratio is an indication of kilograms of water consumed through evapotranspiration to produce one kilogram of plant material. Figures reported are on a plot basis with 250 plants per plot. The ET ratios were lower in 1980 indicating more efficient water use. Hybrids were generally more efficient than their parents. Hybrid four had the greatest grain yield in 1980 and a relatively low ET ratio. Hybrid seven was the largest yielder in 1981. This entry demonstrated extremely efficient water use and high harvest index.

CHAPTER 5

SUMMARY

Six grain sorghum hybrids and their male and female parents were subjected to moisture-stressed and non-stressed conditions during the summer of 1980 and 1981. Environmental conditions at the USDA Plant Materials Center, Tucson, Arizona were more severe in 1980 than 1981.

Soil moisture was monitored semiweekly with a neutron probe to determine water consumption and evapotranspiration rates. Soil moisture under stressed conditions was reduced to 0% available moisture in the first 30 cm of the profile 58 and 55 days after planting in 1980 and 1981, respectively. Water was applied to the irrigated treatment when available soil moisture was decreased to 50%.

Mean cumulative evapotranspiration in the stressed treatment was 270 and 261 mm in 1980 and 1981, respectively. These were equivalent to ET rates of 3.6 and 3.2 mm day⁻¹, respectively. Genotypic differences in cumulative ET was expressed only under irrigated conditions. Male one had the highest cumulative ET in 1980 at 638 mm and the lowest in 1981 at 355 mm. Hybrids were not consistent with respect to parents in water consumption. They exhibited rates both greater and lower than their parents. Mean ET rates for irrigated hybrids were 6.1 and 7.9 mm day⁻¹ in 1980 and 1981, respectively. Erie, French and Harris (1965) reported sorghum mean ET at 8.3 mm day⁻¹ for the same

growth period in the Phoenix, Arizona area. Potential ET on the high plains of Texas is about 850 mm (Jensen, 1968), considerably less than pan evaporation under Arizona conditions (Figs. 2, 3).

Hybrids and female parents reached growth stages four and five before male parents. Irrigation had no significant effect on rate of development but did affect height both years and stem weight in 1980.

Leaf area, as determined by leaf weight and specific leaf weight, was not significantly different between water levels. Genotypic differences for leaf area were observed in 1981 but not in 1980 under both water regimes. Total leaf area was not solely responsible for cumulative water loss. Female five which had the smallest leaf area in the 1981 irrigated treatment (Table 15) lost a considerable amount of water ($13,855 \text{ kg plot}^{-1}$ vs. a mean of $12,539 \text{ kg plot}^{-1}$). Mean seasonal transpiration rate of F5 was also greater than the mean of all entries under irrigation in 1981 (Hofmann, 1982).

Hybrid four had the greatest grain yield under stressed and irrigated conditions in 1980. The same germplasm (H8) was not significantly different in grain yield from H7 which had the highest yield under both water levels in 1981. Hybrids had greater grain yield than respective male parents because of more seeds per panicle rather than increased seed weight.

Harvest index was higher in hybrids. High-yielding hybrids had more stable seed numbers and harvest indexes over moisture regimes. Hybrid four which had the highest grain yield in 1980 consumed 832 kg of water to produce 1 kg of grain on a plot basis. The lowest yielder

in 1980, M3, utilized 3,013 kg water per kilogram grain under irrigated conditions. This range of kilograms water utilized per kilogram grain produced was less in 1981, varying from 1,080 kg H₂O kg⁻¹ grain for H7, the highest yielder to 1,961 kg H₂O kg⁻¹ grain for M6 which had the smallest grain yield.

More water was used in the irrigated treatment. Increased water use did not significantly increase mean grain yield. Hybrids were stable over moisture regimes indicating more efficient irrigation practices coupled with deliberately reduced soil moisture levels could be utilized for substantial economic returns. Stable, high-yielding hybrids could also be used in semi-arid areas which rely totally on rainfall for agricultural production. Invariable moisture deficits would be less detrimental and greater security would be provided with stable germplasm.

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