PERFORMANCE, STABILITY PARAMETERS, GENETIC EFFECTS, AND PREDICTION OF PERFORMANCE IN SINGLE, THREE-WAY, AND DOUBLE-CROSS HYBRIDS OF SORGHUM [*Sorghum bicolor* (L.) Moench]

A Dissertation

by

GEORGE ANTHONY OMBAKHO

Submitted to the office of Graduate Studies
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 1994

Major Subject: Plant Breeding

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ABSTRACT

Performance, Stability Parameters, Genetic Effects, and Prediction of Performance in Single, Three-Way, and Double-Cross Hybrids of Sorghum [*Sorghum bicolor* (L.) Moench]. (May 1994)

George Anthony Ombakho, B.Sc., M.Sc., University of Nairobi, Kenya

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Trials were conducted in Texas, and in Kenya between 1990 and 1993 to evaluate performance and stability of single, three-way, and double crosses of grain sorghum, estimate genetic effects, and evaluate grain yield prediction methods for three-way hybrids. Grain yield heterosis was estimated for single and three-way crosses. Preliminary evaluations were at College Station in 1990, and selected entries evaluated in four environments over two years in Texas. A complete set, excluding reciprocals, of parents, single, and three-way crosses, was evaluated in five environments in Kenya. Genetic effects were estimated from experiments in Kenya.

In Texas, single and three-way crosses differed infrequently for characters studied, while these hybrid-types outperformed double crosses most times. Double crosses were most stable followed by three-way crosses, single crosses, and parental lines, respectively, for grain yield and other agronomic characters. In Kenya, three-way hybrids outyielded fertile single crosses in better environments, and the two hybrid-types showed equivalent performance in other agronomic characters. Sterile single crosses were superior to parental lines in all characters except threshing percentage. Three-way crosses were more stable than fertile single crosses. Better interpretation for yield stability came from logarithm transformed data.

Within-plot variabilities, measured as standard deviations, for plant height, panicle length, and panicle exsertion were higher in three-way and double crosses, but differences were not large enough to be of agronomic importance. High-parent heterosis (heterobeltiosis) in single crosses was higher than in three-way crosses. Sterile single crosses exhibited significant heterosis, important for three-way hybrid-seed producers.

Genetic analyses showed additive and dominance effects to be important in the expression of grain yield, threshing percentage, 1000-seed weight, days to 50% anthesis, plant height, panicle length, and panicle exsertion. However, for grain yield, epistatic effects also were important.

Three-way hybrids grain yield was predicted using estimates of genetic effects. Correlation coefficients of observed and predicted values indicated relative effectiveness of five prediction methods to be in accord with significance of genetic effects included in the prediction equation. Prediction using means of nonparental single crosses was preferable because of its simplicity.

DEDICATION

This dissertation is dedicated to my late father, Michael Odero Oyeyo and my mother, Florah Masakhwe Odero for understanding the value of a good education, and their dedication to educating their four sons and four daughters.

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TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

TABLE PAGE

CHAPTER I
INTRODUCTION

Sorghum [*Sorghum bicolor* (L.) Moench] is an important cereal grain ranking fifth among the major cereals in world food grain production and hectarage, after wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), maize (*Zea mays* L.) and barley (*Hordeum vulgare* L.) (FAO, 1990). Total world sorghum grain production has recently been estimated at 58,190,000 metric tons, harvested from an area of 44,352,000 hectares with an average yield of 1312 kg/ha.

Sorghum is grown under two different farming systems (Group I and Group II) (FAO, 1988). Yields in group I are low ranging from 0.5 to 0.7 tons/hectare and relate to developing countries. Yields in group II range from 3 to 5 tons/hectare and although primarily in developed countries, include some developing countries, particularly in Latin America. Of the total sorghum world production area, over 80% is cultivated in developing countries (FAO, 1990).

In the United States of America (U.S.A.) and other developed countries, sorghum is utilized almost entirely as animal and poultry feed with little human consumption as specialty food products. In Africa and the developing countries of Asia and Latin America, sorghum grain mainly is grown mainly on a small scale by peasant farmers, primarily for subsistence use as human food and beverages, with the residual stalks and leaves being used as fodder for livestock, cooking fuel, and in construction. Sorghum is a major staple food of the semi-arid regions of Africa. The landraces that have evolved in the region have stable but low grain yields when grown under harsh conditions characterized by poor, eroded soils, and low unevenly distributed rainfall. The varieties grown by farmers have low yield compared with other cereals, and though several improved varieties have been developed, the yield gains have been insignificant.

Sorghum hectarage has been reported as expanding more rapidly worldwide than for any other cereals (Munck et al., 1982) due to the crop's excellent adaptation to a wide range of climatic and cultural conditions. Sorghum is adapted to the semi-arid tropical, sub-tropical and temperate regions between 45° N and 45° S. Although it responds to irrigation (Musick and Dusek, 1971), it also performs well on dryland, especially when soil water is not limiting at planting, and rainfall is near normal during the growing season (Unger, 1984; Unger and Wiese, 1979). Sorghum grain yields on dryland, however, can be reduced sharply by water stress during critical reproductive growth stages (booting, flowering, grain filling).

Grain sorghum is commonly grown in water-limited environments where water-use efficiency and drought resistance traits play major roles in the successful adaptation of new

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This dissertation follows the format of Crop Science.

cultivars.Because of sorghum's importance as a world cereal, unique adaptation to stressful environments, and broad genetic diversity (Mann et al., 1983), it should provide an important economic base for Africa, where increasing food deficits are being experienced, and play a major role in alleviating food shortages as population growth increases. Many factors affect the volatility of sorghum production, the most significant, perhaps, is the use of the crop under often stressful conditions such as in the semi-arid tropics or the Great Plains of the U.S.A. In developing countries, with the exception of India, Thailand, Zimbabwe, Nicaragua, and Colombia, the use of hybrids remains negligible (Maunder, 1990). In these areas, most of the breeding procedures used in sorghum are aimed at maximum exploitation of hybrid vigor for both grain and forage yields.

Sorghum is an important cereal in Kenya. It ranks second to maize in production, which is estimated at 145,000 metric tons annually, on a harvested area of 140,000 hectares, and an average yield of 1036 kg/ha (FAO, 1990). Yields, which can be as low as 600 kg/ha, are attributable to the use of locally adapted traditional cultivars with little use of fertilizers, crop protection or improved tools by peasant farmers (Gebrekidan, 1987). The absence of, or inadequate policy support, for example, price and marketing structures along with physical constraints, result in sorghum being considered a subsistence crop in many developing countries. As such, necessary inputs for increased production are less likely to be a component of the resource management strategy (Maunder, 1990). Sorghum is widely grown in the marginal rainfall areas of Eastern Kenya and in the Lake Basin region of Western Kenya.

Sorghum improvement in Kenya was started by the regional East African Agriculture and Forestry Research Organization (E.A.A.F.R.O.) in the 1950's (Doggett, 1986). A national sorghum and millets improvement program was established for Kenya in 1977. The sorghum improvement program has objectives aimed at two diverse ecosystems: (i) for Western Kenya, to develop superior cultivars coupled with an improved agronomic package, aimed at optimizing and stabilizing sorghum yields; and (ii) semi-arid (marginal areas) of Eastern Kenya, to develop varieties with high and stable yield and early maturity (Rutto, 1990).

The production of hybrid seed on a commercial scale in self-pollinated crops such as sorghum has been possible through the use of cytoplasmic-genetic male sterility. Sorghum hybrids utilized are single crosses since inbreeding in sorghum does not reduce yields as drastically as in maize. In maize, seed yield of inbred lines is about one-third of the original stock because of inbreeding depression (Jones, 1939), resulting in considerable costs in seed production. In sorghum, inbreeding depression also occurs but to a lesser extent. Cytoplasmic genetic male-sterile inbred lines of sorghum have been developed with reasonably good yields. Single cross hybrids maximize heterosis (between 20 to 40% over best parent) but may have narrowed ranges of adaptation due to genetic homogeneity. The main advantage of single cross hybrids is their uniformity in agronomic characters which may make for easier harvest and application of insecticides. Disease resistance also may be easier to incorporate. Three-way and double cross hybrids may suffer from slight reductions in yield but the modest degree of genetic heterogeneity may provide substantially increased ranges of adaptation and thus stability over a wide range of environments.

The sorghum growing areas of Kenya are variable, covering 3 of the 6 ecological zones (Rutto, 1990). These sorghum growing areas are so diverse that multi-cross sorghum hybrids may be promising if they are able to provide a "buffer" against the diverse adverse environments. The possibility of them performing in a consistent manner over a range of environments is worth considering. Three-way cross hybrids may find their greatest usefulness in lower yield production areas. Late planting, which is common among sorghum farmers in Kenya, should be considered low yield production. Furthermore, the production costs involved in providing planting seed to farmers would be significantly reduced with the use of F_1 hybrids as parents. Hookstra and Ross (1982) suggested that use of F_1 female parents in sorghum hybrids can reduce production costs to the seed producer and seed costs to the farmer if acceptable, high performing hybrids are identified. An inventory of fewer hybrids would have to be maintained by the seed companies since the multi-cross hybrids would have a wider range of adaptability. Techniques for efficiently predicting the performance of these hybrids in lieu of producing and testing all hybrid combinations would certainly appear attractive to sorghum breeders. The stability of crop yield is a more serious problem in less developed than in developed countries (Eberhart and Russell, 1966). Information on the types of gene effects associated with yield responses of sorghum hybrids should be of value, especially in relation to a fuller understanding of the potentials of different hybrid populations and their expressions of heterosis and to the possibility of breeding for a desired level of yield stability.

The objectives of these studies were to (i) evaluate the relative performances of different types of sorghum hybrids, (ii) analyze environmental responses of the different sorghum hybrid types and their stability, (iii) estimate certain genetic effects present in a fixed set of lines, and (iv) evaluate different yield-prediction methods for three-way cross hybrids.

CHAPTER II
LITERATURE REVIEW

Sorghum breeders made few advances in improving sorghum yield potential until an economical large-scale method of producing hybrids was devised. Utilization of hybrid in self-fertilizing species requires conversion of the mating system to outcrossing by the use of male sterility. The utilization of heterosis in sorghum was made possible initially through three-way cross hybrids produced by use of a genetic-type male sterility (Stephens et al., 1952). A cytoplasmic-genetic male-sterility, and fertility-restorer system was then discovered (Stephens and Holland, 1954) and the first single cross hybrids were released. The cytoplasmic-genetic system outlined by Stephens and Holland (1954) made hybrid sorghum commercially feasible. Cytoplasmic male sterility is readily available, as are sources for pollen fertility restoration. Three-way cross hybrids also can be produced with this cytoplasmic male sterility; double cross hybrids are commercially unfeasible because of segregation for male sterility. Fazlullah Khan (1991) has developed a new method for commercial production of double cross hybrid seed that overcomes the segregation problem. The sorghum hybrids grown are generally single cross F_1's. Less than 2% of the total production of grain sorghum in the United States had been reported as coming from three-way cross hybrids (Harvey, 1977).

The *milo/kafir* system of cytoplasmic-genetic male-sterility (Stephens and Holland, 1954), in progeny with *milo* cytoplasm and nuclear genes from a *kafir* type, has been the principle source of male sterility for hybrid sorghum seed production. Harvey (1977) surveyed hybrid sorghum seed industry and found that females of *milo-kafir* origin accounted for 97.1% of the grain hybrid seed production. The vulnerability of a crop dependent upon a single cytoplasm received national attention in the U.S.A. in 1970 and 1971, when maize hybrids produced on T-cytoplasm male-sterility seed stocks dramatically succumbed to southern corn leaf blight, caused by *Helminthosporium maydis* Nisik and Miy. Hybrids retaining the plant's normal cytoplasm showed only limited symptoms. Although vulnerability to disease is a most likely hazard, others might exist.

In addition to the initial *milo/kafir* (A_1) male-sterility system, there have been reports of alternative male-sterility cytoplasms, identified through differential sterility responses (Schertz and Pring, 1982; Rao et al., 1984). Among these alternative cytoplasms, A_2 derived from the Ethiopian line IS12662C was released in Texas (Schertz and Ritchey, 1978) and has since been incorporated into elite lines that could be used directly in commercial hybrid seed production. This represents a system genetically different from the conventional *milo-kafir* complex. Kishan and Borikar (1988) evaluated sorghum hybrids involving three iso-sterile (A_1, A_2, and A_4) lines and concluded that the exploitation of A_2 cytoplasm was desirable. Alternative male-sterility inducing cytoplasms are necessary to avoid disease and environmental hazards that might be cytoplasm-specific, and to add nuclear diversity by using new parental combinations which are not possible in the *milo/kafir* system. These alternative cytoplasms should increase the prospects of three-way cross hybrids.

The incorporation of some level of variability in hybrid sorghum production through the use of multi-cross hybrids other than single cross hybrids could be beneficial; single cross hybrids are homogeneous and therefore specific in response to environment resulting in increased yield losses under poor environmental conditions. The stability of crop production, i.e., the relatively constant annual yield of a crop grown by a farmer, is one of the most important issues facing world agriculture and food production; in some cases, stability is equally as important as yield itself. Stability is influenced by a cultivar's genetics, the environment in which it is grown, and the cropping system used in the environment. Across a diversity of these three factors, growers, marketers, consumers, and policy makers are confronted with the problems of dependability and predictability of food supply.

In intensive cropping systems, commonly practiced in developing countries, like Kenya, stability is of paramount importance if growers are to feed the family and community. In these countries, intercropping is a frequent system of choice because it ensures more production stability and more diversity of food for the diet (Francis, 1981; Federer, 1993). Reliability of crop yields is always a problem, and it can be more serious in developing than in developed countries, where advanced technology can be used to modify environmental impacts. Multi-cross hybrids provide the necessary diversity for yield stability through populational as well as individual buffering (Allard and Bradshaw, 1964). In a developing country like Kenya, the impact of a crop failure may be even greater and the resources for quick response are inevitably lacking. A concomitant question facing plant breeders has been what type of population structure or hybrid type is most desirable in order to optimize chances of combining high yield performance and satisfactory yield stability.

Performance and Prediction of Performance

Comparisons of performance of three-way with single cross sorghum hybrids were first reported in Texas in 1959 (Stephens and Lahr, 1959). The mean yield of the three-way cross hybrids was 2% higher than that of the single cross hybrids over 2 years. Yields of three-way hybrids and related single cross hybrids of sorghum were also evaluated in Kansas, under dryland conditions over a 4-year period (Ross, 1969). The overall mean yields of the two types of hybrids did not differ significantly, but significant differences were obtained in 2 of the 4 years between single and three-way crosses. Three-way hybrids had lower yields than the single crosses in a poor year, but were more productive in a year characterized by high yields. In another Kansas study (Ross, 1972) three-way hybrids had significantly higher mean yields than the single cross hybrids. Jowett (1972), in a study involving a series of sorghum trials in East Africa, with one site at Kampi ya Mawe in Kenya, reported no significant difference between single crosses and three-way cross hybrids. Walsh and Atkins (1973) examined the mean performances of three-way and single cross hybrids in a 2-year study in Iowa and found nonsignificant differences for grain yield, seed weight, plant height and days to anthesis among other characters. The significant differences for yield and several other attributes among single crosses, and among three-way hybrids, were due largely to differences in general combining ability (g.c.a.) of the male and female parents. Walsh and Atkins (1973) reported that the differences among the sterile single crosses for the genetic contribution to the three-way hybrids were due primarily to differences in g.c.a. of their parents. Similarly, in Iowa (Patanothai and Atkins, 1974a), a 3-year study indicated equivalent mean yields over nine environments for fertile single cross F_1 hybrids and three-way cross hybrids. Both hybrid-types yielded significantly more than the male-sterile single cross hybrids and the parental lines.

The main advantage of single cross hybrids is their uniformity in agronomic characters which makes for easier harvest and application of insecticides. Disease resistance also is easier to incorporate. Within-hybrid variability often is visible in multi-cross sorghum hybrids and can be of concern to farmers (Hookstra and Ross, 1982). Walsh and Atkins (1973) examined within-hybrid variability of three-way and single cross hybrids of sorghum for plant height and days to 50% anthesis, and reported greater within-plot standard deviation for both characters in the three-way cross hybrids. This variability, however, did not seem large enough to cause practical problems at harvest. Much earlier, Stephens and Lahr (1959) had concluded that single cross and three-way cross hybrids needed not to differ markedly in plant-to-plant variation for height and maturity. Considering all possible hybrids from a given sample of inbred lines, there is a decline in expected genetic variance and consequently in the highest predicted yield potential from single to three-way to double to top crosses (Cockerham, 1961).

Hookstra and Ross (1982) recommended the use of F_1 sterile females as parents in grain sorghum hybrid seed production, since this can reduce costs to seed producers and, eventually seed costs to the farmer. Few seed production studies comparing the use of sterile F_1's (A_i X B_j) and inbreds (A_i) as parents for hybrid seed production have been reported. Stephens and Lahr (1959) demonstrated the seed production advantages of sterile F_1's over lines and showed that the F_1 sterile hybrids outyielded the lines by an average of 70% over 2 years. The hybrids also set more seeds per panicle in 130 of 135, and in 63 of 66 comparisons. Similar results were reported in subsequent studies (Rosenow, 1968; Ross, 1972; Walsh and Atkins, 1973; Patanothai and

Atkins, 1974a; Ross and Kofoid, 1978; Hookstra and Ross, 1982) in which the mean seed yield of the male-sterile F_1 hybrids ranged from 3 to 30% over the means of the male sterile A-lines used as parents. Results from Hookstra and Ross (1982) indicated a 54% superiority of the F_1 sterile hybrids over the component A-lines in grain yield. The differential was attributed to increases in seeds per panicle (52%), panicles per plant (3%), and threshing percentage (7%). Yield heterosis is expressed by a higher threshing percentage and increased grain production, the latter coming largely from an increased number of seeds per panicle (Quinby, 1974).

Double, three-way, single, and modified single cross hybrids are used in commercial maize hybrid seed production. In maize, Anderson (1938) found that the performance of a three-way hybrid corresponded closely to that of the mean of the two single-cross counterparts. Weatherspoon (1970) compared the performances of single, three-way and double cross maize hybrids and reported average yield superiority in that order, explaining this relationship to be due to the more complete utilization of both the dominance and epistatic effects in the single and three-way cross hybrids than in the double cross hybrid. In a detailed study using maize yield data compiled from 10 published experiments, Schnell (1975) found relative average yields to mostly decrease from single crosses towards double crosses, but exhibiting non-linear trends in that three-way crosses averaged up to 1.7% more than the single crosses. Schnell (1975) concluded that under conditions "hitherto" not fully understood, three-way crosses could have average superiority to single cross hybrids. Reports on the performance of the different types of hybrids in other crops; rye (*Secale cereale* L.) (Becker et al., 1982), sugarbeet (*Beta vulgaris* L.) (Skaracis and Smith, 1984), cotton (*Gossypium hirsutum* L.) (Shroff et al., 1988) and sunflower (*Helianthus anus* L.) (Dedio, 1992) all indicated nonsignificant differences in yield between single cross and three-way cross hybrids. Becker et al. (1982) reported three-way cross mixtures of rye as having a slightly higher yield than the three-way crosses which indicated that an increase in heterogeneity had a positive rather than a negative effect on yield.

The large number of possible three-way and double cross combinations makes the testing of all lines developed in a breeding program impossible. Given that N_1 represents the number of male sterile inbred lines and N_2 the number of restorer pollinators to be combined with the sterile single cross F_1's among the inbreds, then $[N_1(N_1-1)/2 \times N_2]$ distinct three-way cross hybrids are possible with the assumption of no reciprocal differences in the single crosses. Prediction of performance for three-way and double cross hybrids from the average performances of respective single crosses can be a helpful tool for the production of selected promising multi-cross hybrids more extensively.

The bulk of the theory and experimental documentation concerning methods for the prediction of three-way and double cross hybrid performance have been developed in relation to maize. Jenkins' (1934) classical study proposed four methods of predicting double cross grain yield means. The methods presented for the predictions of double-cross from single cross means in brief included: (A) the mean value of all the six possible crosses among the four lines in the double cross; (B) the mean values of the four nonparental single crosses; (C) the mean of the "means of all crosses" for the four parental lines of each double cross in all combinations with 10 other lines; and (D) the mean values of the four lines in top crosses. Jenkins (1934) reported correlations of 0.75, 0.76, and 0.73 for the first three methods respectively on his yield data, and showed that the yield of the double cross, $D_{ij,kl}$ could be predicted by the average performance of the nonparental single crosses (method B), i.e., $\frac{1}{4}(S_{ik}+S_{il}+S_{jk}+S_{jl})$. The method B has been extended to include three-way crosses in which the mean of the two nonparental single crosses is used to predict each three-way cross mean: $T_{ij,k} = \frac{1}{2}(S_{ik}+S_{jk})$ (Eberhart et al., 1964).

The concern over the error which epistasis could introduce into the predictions, led to the development of considerably more complex predictive procedures (Eberhart and Hallauer, 1968; Otsuka et al., 1972; Stuber et al., 1973). These procedures were based on genetic analyses according to specific models. Furthermore, models also were developed to account for genotype X environment interactions (Ottaviano and Gorla, 1972), and even for the specific conditions of a particular experiment (Cockerham, 1967). Cockerham (1967) presented a general equation for predicting double cross performance by using a linear combination of uncorrelated single cross means weighted with the optimum values selected to minimize the variance of the prediction error. Skaracis and Smith (1982) investigated the relative magnitudes of different types of effects present in a fixed set of sunflower lines following the general fixed effects model (Gardner and Eberhart, 1966; Eberhart and Gardner, 1966). The effects were then used in three of their five prediction methods while the fourth and fifth methods utilized the averages (unweighted and weighted) of the parental single crosses and pollinator to predict the three-way cross hybrid means. The conclusion in most of these studies was that practical limitations (complexity, experimental errors, genotype X environment interactions) rendered these complex procedures not advantageous over Jenkins' (1934) method B.

The use of nonparental single crosses and of three-way crosses has been reported to give double-cross predictions unbiased by additive and dominance effects. However, epistatic effects in some of the three-way and double-cross hybrids may result in a bias in the predictions (Eberhart, 1964). The estimated deviation of observed performance from predicted performance also was suggested to be a very useful measure of the relative importance of epistasis. The mean of the nonparental crosses is still considered the best and most practical, and the concept of prediction has been extended efficiently to crops other than maize (Patanothai and Atkins, 1974b; Skaracis and Smith, 1984; Jha and Khehra, 1988).

Stability Analysis and Stability Parameters

The term "stability" has been used in several attempts at the interpretation of the genotype by environment (GE) interaction. The concern for stability has been due to the importance of homeostasis in living organisms and the awareness by plant breeders of the need to develop well-buffered cultivars, leading to greater emphasis on phenotypic stability in breeding programs. Concepts of genotypic stability are either biological or agronomic (Becker, 1981). Biologically, a genotype with minimum total variance under different environments is considered stable (Hanson, 1970). An agronomically stable genotype has a minimum interaction with environments but responds favorably to improving environments (Eberhart and Russell, 1966). Several definitions have been given according to these concepts (Marquez-Sanchez, 1973; Francis and Kannenberg, 1978; Lin et al., 1986). Lin et al. (1986) classified stability into three types. Type 1 stability follows the biological concept and is measured by the minimum variance across a range of environments. A genotype is considered to have Type 2 stability if its environmental response is parallel to the mean response of all cultivars in the test. Type 3 stability is indicated when the mean squares for deviation from regression of a genotype is negligible. Type 4 stability was designated by Lin and Binns (1988), who proposed variance of genotypic means across unpredictable environments (years) averaged across predictable environments (locations) as a new stability parameter.

The choice of cultivars as potential varieties or hybrids in a plant breeding program generally is based on the superiority in performance over a wide range of environments. Similarly, for a trait or parameter to be useful in the selection of superior cultivars, it must be genetically controlled and should be repeatable across samples of the environments for which selections are made. Stability of production in the range of environments covered by a particular crop is an important consideration of any crop breeding program. Extensive testings are therefore typical, to assist in identifying ideal cultivars that show minimum interaction with environments thereby possessing the greatest yield stability. Definitions for stability have included two major parts, (i) biological stability or homeostasis, i.e., minimal entry variance across environments (Becker, 1981) and (ii) response or relative performance over environments. A working definition of stability has been given (Saeed and Francis, 1983) as adaptation to a wide range of growing conditions in a given production area, with above average yield and below average variance across environments.

Development of grain yield in sorghum is complex because of the multiplicative nature of yield components and the temporal influence of climate on their expression. Two main components, number of seeds and seed size, determine the final yield though other subcomponents can affect yield through their effects on these main components. Eastin and Sullivan (1974) noted three stages of plant growth critical to yield in sorghum: GS1 (planting to panicle initiation), GS2 (panicle initiation to anthesis), and GS3 (anthesis to physiological maturity). They reported that events in GS2 are important to potential number of seeds, while those in GS3 directly affect seed size. The causes of yield stability often have been described as unclear, with a diversity of physiological, morphological, and phenological mechanisms imparting stability. Heinrich et al., (1983) categorized the mechanisms of stability into four general parts: genetic heterogeneity, yield component compensation, stress tolerance, and capacity to recover rapidly from stress. Tolerance to problem soils and resistance to pathogens and insects are examples of stress tolerances that enhance stability (Mahadevappa et al., 1979; Webster, 1972). Research with rice (*Oryza sativa* L.) indicated that drought resistance and capacity to recover from drought are necessary for yield stability (IRRI, 1977).

Yield components are developed in a series of sequential events that involve various metabolic and developmental activities. The effect of stress due to environmental factors on the final yield may, therefore, vary depending upon the growth stage in which it occurs.Grafius (1957) defined yield as a product of the several yield components including seed weight and noted that reductions in one component may be compensated, to varying degrees, by an increase in other yield components, and depending on temporal development of these components, there is a tendency to stabilize yield. Because yield is a product of yield components, and these generally are the product of sequential development processes, the timing of critical stresses may be specified by examining yield component functions. Susceptibility to stress could be indicated by reductions in the yield component developing during the period of stress, and tolerance or compensation by a nonstressed yield component. Sorghum cultivars generally show differential yield response to varying environments (Liang and Walter, 1966; Saeed et al., 1984), which indicates a differential effect of environments on yield component development. Although possible reduction in yield caused by reduction in a certain component can be compensated for to a certain extent by a concurrent increase in another component (Stickler and Wearden, 1965), yield may still be limited by unfavorable environmental effects. Heinrich et al. (1983) found tolerance of stable cultivars to stress conditions, and the maintenance of yield components at relatively high levels, more important than compensation among the components. Consistently higher seed weights of stable sorghum cultivars seemed to contribute to yield and to stability and they recommended breeding for more seeds/panicle and greater seed weights would be useful.

Evaluation of cultivars for consistency of performance in different environments is important in plant breeding programs. The range of environments encountered in practice should be included in experiments studying the concept of stability (Federer and Scully, 1993). The relative performance of cultivars often changes from one environment to another. The occurrence of a large genotype x environment (GE) interaction poses a major problem of relating phenotypic performance to genetic constitution and makes it difficult to decide which cultivars should be selected (Comstock and Moll, 1963). GE interactions can therefore reduce the progress of a breeding program if the test environment is not representative of the target environment. Differential yield responses of cultivars can be caused by differences in phenology. Various techniques have been developed to evaluate genotype stability over a range of environments in many crops. The study of GE interaction requires some measure of environments. Environmental data such as temperature, available moisture, nutrient supply, rainfall pattern, air movement, etc., are not sufficiently precise to be reliable in such studies. A simple, easily obtained numerical value was needed. A widely used technique for assessing stability has been the regression approach which describes the performance stability of a genotype in terms of linear regression of genotype means over environmental means. The technique for examining the GE interaction was first proposed by Yates and Cochran (1938). This technique was amplified and used by Finlay and Wilkinson (1963), to analyze the adaptation of 277 barley cultivars grown in a range of environments, who proposed the average yield of all cultivars grown at a particular site in a particular season as a measure of that environment.

Eberhart and Russell (1966) later refined the technique and suggested the use of two statistics, the linear regression coefficient (b_i) and the mean square deviations from linear regression coefficient (S^2_{di}), to estimate stability. They used an environmental index (I_j) to measure environments instead of the actual mean yield. The indices (I_j's) were formed by subtracting the mean yield of all cultivars in all environments from the mean of all cultivars in each environment. A regression analysis, in which the cultivar means are regressed against the environmental indices, provides a method of comparing the mean relative response of a particular cultivar to mean response of all cultivars. Any significant deviation from the average response (regression coefficient, b_i=1.0) can be considered a GE interaction, although it may be a predictable response to either good or poor environments. The mean square for deviations from regression (S^2_{di}) was suggested by Eberhart and Russell (1966) as a measure of the predictability of the GE interactions. Becker et al. (1982) regarded this parameter as the most appropriate criterion of phenotypic stability in an agronomic sense. They proposed that the slope of the regression (b_i) indicates the responsiveness of the genotype to environmental fluctuations. The regression coefficient is generally closely correlated with the environmental variance (Becker, 1981). Joppa et al. (1971) defined the magnitude of S^2_{di} as an excellent indicator of specific GE interactions. Samuel et al. (1970) and, Paroda and Hayes (1971) emphasized that linear regression could simply be regarded as a measure of response of particular cultivars, whereas the deviation around the regression line (S^2_{di}) is the most suitable measure of stability, cultivars with the lowest standard error (Sb) or deviation around the regression line (S^2_{di}) being the most stable and vice versa.

According to Wricke and Weber (1980), as cited by Becker et al. (1982), in crops, the deviation mean squares generally explains most of the total GE interaction mean squares.

Several workers have adapted the technique with slight modifications (Perkins and Jinks, 1968; Shukla, 1972; Langer et al., 1979). Other techniques which do not employ regression such as the genotype grouping technique (Francis and Kannenberg, 1978) and cluster analysis (Lin et al., 1986), in which cultivars are grouped according to their response structure, are also available. Many clustering strategies have been applied, but the particular choice can result in different cluster groups and may give misleading results (Westcott, 1986). Cluster analyses have been suggested as appropriate for identifying varieties that have similar characteristics to a control cultivar (Lin et al., 1986). Lin et al. (1986) have reviewed the statistical formulae, applications, and relationships of nine stability statistics and nine similarity measures. The GE interaction can therefore be partitioned by parametric linear regression techniques (Finlay and Wilkinson, 1963; Eberhart and Russell, 1966) or multivariate techniques (Kempton, 1984; Lin et al., 1986; Zobel et al., 1988; Nachit et al 1992).

Since genotype responses are multivariate rather than univariate, the multivariate techniques for GE partitioning have been suggested as preferable (Lin et al., 1986) and in general more effective in explaining GE interactions than linear regression models (Zobel et al., 1988; Nachit et al., 1992). Apart from the determination of the stability of cultivars, these techniques also assist in the identification of cultivars that respond to environmental change, and therefore are more likely to give satisfactory returns to added inputs such as fertilizers or pesticides. The model by Eberhart and Russell (1966) has been used more extensively in crop breeding programs while most of those others proposed and reviewed (Lin et al., 1986) have seldom been used.

Most studies of yield stability in grain sorghum have involved the determination of stability in relation to heterozygosity level. There is an increasing genetic heterogeneity among plants within a cultivar from three-way to double to top cross, so that the reverse of the situation reported by Cockerham (1961) on predicted yield potential is true for yield stability. In numerous studies, heterogeneous plant populations turned out to be better buffered against environmental fluctuations (for review see Simmonds, 1962). In maize, Sprague and Federer (1951) reported that GE interactions were larger for single crosses than for double crosses, and Eberhart et al. (1964) found higher genotype X year interactions in single crosses than in three-way crosses. Hühn and Zimmer (1983), in a study of the phenotypic stability of double crosses vs three-way hybrids of maize varieties used for silage, found a stability superiority of the three-way crosses. Majisu and Doggett (1972) indicated that highly heterotic and stable sorghum hybrids would be able to show large yield advantage over equally stable cultivars. Contradicting evidence indicating stability of three-way and double cross hybrids over single cross hybrids in their performance over a range of environmental conditions has been indicated in the available literature for sorghum, other cereals and non-cereal crops. In grain sorghum, populations with a broad genetic base were found to be more stable than single cross hybrids (Kofoid et al., 1978; Patanothai and Atkins, 1974a; Reich and Atkins, 1970). However, Jowett (1972), from results obtained in East Africa, reported that among single crosses, three-way crosses, and lines of sorghum, hybrids were more stable with no difference between three-way and single crosses in terms of comparing regression coefficients of yield on environmental index. Weak evidence was presented that indicated three-way crosses may be more stable than single crosses in terms of deviations from regression. Becker et al. (1982) found phenotypic stability in rye to increase from three-way to top crosses and that selection for hybrids with high and stable yield was more promising among three-way crosses than among double crosses.

Gama and Hallauer (1980) compared interpopulation and intrapopulation single-cross hybrids of maize produced from selected and unselected lines and detected significant hybrid-environment interactions for both groups. They suggested that selection for mean yield across environments should be emphasized first, and then the relative stability of the elite hybrids over environments should be determined. Heinrich et al. (1983) evaluated yield and components of yield of stable and unstable grain sorghum cultivars to determine the mechanisms important to yield stability. Although the stable and unstable cultivars had comparable yield potential in good environments, the stable types were higher yielding in poor environments, showing that high yield potential in favorable environments and yield stability were not mutually exclusive. Yue et al. (1990) also reported negative correlations between mean yields and stability parameter, b_i , in maize and sorghum, suggesting that high yield and stability were not mutually exclusive. Thus maize and sorghum hybrids with high yield potential and high stability can be identified and selected. Correlations between mean yield and b_i were positive and significant in their study. Scott (1967) had shown that yield stability in maize is genetically controlled and , thus suitable for selection. Eberhart and Russell (1966) reported stability in maize to be a property of the inbred parent lines and suggested the possibility of selecting hybrids that possessed high-yielding capability and interacted less with the environment.

Francis et al. (1984) studied the effects of planting time on yield stability of sorghum hybrids and random-mating populations and reported both stable in late planting than in early planting. Hybrids were relatively more stable than populations in early planting but the reverse was true in late planting. Saeed and Francis (1983) indicated that when cultivars under test include a wide range of maturity, the differences in yield stability among them were largely a function of relative maturity.

Ross (1969) evaluated and reported variances of three-way cross hybrids to be lower than those in single crosses indicating stability for three-way crosses. Significantly greater within-plot standard deviations for plant height and days to 50% anthesis were reported for three-way crosses than those of single crosses (Walsh and Atkins, 1973), but this did not, however, present harvesting difficulties. The variability exhibited by the parents was due largely to environmental, rather than genetic, causes while in the three-way crosses, the differences in variability were, to a significant extent, due to specific as well as general combining ability effects of the parents (Walsh and Atkins, 1973). York et al. (1974) recommended that the R-lines to be used as males in crossing to the sterile-F_1 for the three-way hybrid production should be selected to provide for uniformity and panicle appearance; and that use of seed-parent lines of same seed coat color with the R-line would prevent segregations in seed color in the three-way cross hybrid. Walsh and Atkins (1973) proposed that variability within a three-way cross might result from differences between parents of the male-sterile single cross or from heterogeneity within the parental lines (resulting from relic heterozygosity, mutation, outcrossing, etc); and suggested that if the predominant cause of high variability was a pronounced difference between parents of the sterile single cross, then three-way hybrids showing excessive variability might be avoided by not using diverse parents in the sterile single cross. Rosenow (1968) also suggested that considerable care should be exercised in selecting parents for producing male-sterile single cross hybrids of sorghum so that the resulting three-way hybrid will not be excessively variable. When highly diverse parents are involved in hybrid combinations, or when complementary gene actions are a factor in the expression of specific characters, this caution most likely is warranted.

Genetic Effects and Yield Heterosis

The nature and type of gene action contributing to heterosis is important when single and three-way hybrids become more common in commercial production. Knowledge concerning the inheritance of quantitative traits should increase the effectiveness of selection of these traits. Although individual gene effects are not measurable in quantitative characters, statistical procedures have been developed and used to obtain basic genetic information by considering such genes as a whole. Estimation of various types of gene effects, including epistasis, is of value because it provides information useful in choosing the most appropriate breeding procedures for further crop improvement.

Eberhart (1964) presented a model that partitioned means of all possible single, three-way, and double-cross hybrids derived from a fixed set of four lines in terms of additive, dominance, and digenic epistatic effects under assumptions of normal diploid inheritance, no multiple allelism, no linkage, and no reciprocal effects. He also proposed a method of predicting performance when epistasis must be considered. Eberhart and Gardner (1966), and Gardner and Eberhart (1966) proposed a general model for estimation of fixed genetic effects which permits multiple alleles. The model was considered superior to the model and analyses proposed by Eberhart (1964).

Favorable epistatic combinations of genes in inbred lines may be important in contributing to heterosis in F_1 hybrids. If these favorable epistatic combinations of genes, however, become fixed in the inbred lines during the selection process, the opportunity for recombination would not be present in production of single cross hybrids. On the other hand, because of recombination in single crosses that would be used as parents in the production of three-way and double cross hybrids, yields of three-way and double cross hybrids might be expected to be less than the single crosses (Eberhart and Hallauer, 1968).

Genetic studies reported in sorghum differ, Liang and Walter (1968) found dominance, and the additive X additive (aa) and dominance X dominance (dd) epistatic gene effects to be important in the inheritance of most traits. The magnitude of (aa) epistatic gene effects was comparable to that of dominance gene effects but greater than the additive gene effect. Additive X dominance (ad) epistatic gene effects were of minor importance. Liang and Walter (1968), therefore, stated that the effects of epistasis cannot be considered negligible and warned that genetic models assuming negligible epistasis may be biased. Malm (1968) reported that both general combining (gca) and specific combining ability (sca) effects were of importance in the expression of grain yield. The gca effects were 20.1 times greater than the sca. effects, indicating the importance of additive gene action in yield performance. Ross (1969) found epistasis to be of little importance. Patanothai and Atkins (1974b) reported both additive and dominance gene effects to be important and agreed with Ross (1969) on epistatic effects.

Finkner et al. (1981) investigated the inheritance of grain yield in sorghum and reported that it was determined by dominant or overdominant gene action. Partitioning of the genetic variance indicated that additive gene action was more important than nonadditive gene action. Bittinger et al. (1981) studied genetic variability in a diverse random-mating population of sorghum for various characters: including flowering, height, seed weight, panicle length, and grain yield. Additive genetic variance was greater than dominance variance for all traits except yield. They suggested that complete dominance or overdominance may be operating for some genes associated with yield.

Quinby and Karper (1945) found that time of floral initiation in sorghum controlled the number of leaves, duration of growth, and ultimate plant size. Quinby (1966) reported four gene loci affecting time of floral initiation; both dominant and epistatic effects appeared to be involved, and there was evidence of multiple alleles at one locus. In general, recessiveness results in earlier maturity. Earlier, Quinby and Karper (1954) had reported four independently inherited major genes controlling height in sorghum. Each additional recessive locus resulted in reduced internode length. The maturity genes also influence height by controlling the number of internodes. Hadley (1957) analyzed the variation of height in a cross between 'Double Dwarf White Sooner' milo and 'Durra P.I. 54484', and indicated that at least four independent genes with unequal effects controlled height. Incomplete dominance was indicated.

Seed size is quantitatively inherited in sorghum and gene effects are largely additive (Beil and Atkins, 1967; Bittinger et al., 1981; Fanous et al., 1971; Jan-Orn et al., 1976; Lothrop et al., 1985a). Nonadditive gene effects also may contribute to the variation in seed size (Kirby and Atkins, 1968; Liang and Walter, 1968; Niehaus and Picket, 1966). In an inheritance study of reciprocal crosses of sorghum and sudangrass, Lamb et al. (1987) reported that the additive genetic effect was most important for seed weight, accounting for 53% of the variation among entries and generations. Dominance effects and deviations from the model (dominance types of epistasis) accounted for much of the remaining variation. Similar results had been reported by Voigt et el. (1966) who, investigating the inheritance of seed size in crosses between small and large seeded sorghum varieties, found that additive effects accounted for almost all of the variation among generations. Dominance effects were significant in that study also, but accounted for a very small fraction of the variation among generations. Lothrop et al. (1985b) reported results indicating that seed weight is controlled primarily by additive gene effects, and that it exhibits small GE interaction. Malm (1968) reported both gca and sca to be important in the expression of seed weight, however, gca effects were 64.1 times greater than sca effects indicating predominance of additive gene action.

Increased seed size in sorghum may be important in an improvement program. Potential benefits may include increased grain yield, increased germination percentage, and improved stand establishment. The lack of agreement among several of these studies was, no doubt, due to differences in the lines or cultivars used, conditions of growth and the differences in the models adapted.

Heterosis has been observed in many self-fertilizing species and has been the object of considerable study as a means of increasing productivity of sorghum and other cereals. Heterosis (defined here as an advantage of the hybrid over the best parent - otherwise called heterobeltiosis) is unexplained on both physiological and genetic grounds (Blum et al., 1990). Heterosis in sorghum can be summarized from the only comprehensive review on the subject (Quinby, 1974) and some subsequent reports by others. Quinby (1963) found that heterosis was expressed by earlier anthesis, increased height, large stems, larger panicles, higher threshing percentage, and greater production of grain and forage. The increase of grain yield was due primarily to a greater number of seeds per panicle, which has been reported as the most important of yield components (Stickler and Pauli, 1961; Quinby, 1963). Blum (1970) reported heterosis for grain yield to result mainly from a large number of kernels per panicle, mostly in the lower panicle branches. The large panicle in the hybrid is initiated earlier and develops faster than its parents. Hybrids therefore flower several days before their parents. They also manifest heterosis for plant height. Blum et al. (1989) reported significant heterosis for biomass, grain yield per plant, and kernel number per panicle. No heterosis occurred for harvest index, indicating that heterosis in grain yield was due to heterosis in biomass. Sorghum hybrids produce more biomass when compared to their parents (Quinby, 1974). With about the same harvest index as their parents hybrids, therefore, produce more grain.

Several publications (Stephens and Quinby, 1933; Quinby and Martin, 1954) indicate that heterosis exists without contrasting alleles of major genes for maturity and/or height. Whitehead (1962) demonstrated that F_1's of an array of crosses yielded 74% more grain than the average of the parents. This level of heterosis occurred only when lines having contrasting height genes and, presumably, great genetic diversity were crossed. It was suggested that total genetic diversity rather than simply the effects of the contrasting height genes was primarily responsible for the hybrid vigor obtained. Quinby (1963) suggested that heterosis in sorghum probably involves complementary action of alleles as well as complementary action of non-allelic genes. Niehaus and Pickett (1966) observed that heterosis was most striking when one of the parents was an introduction. Bailey, Jr. et al. (1980) investigated heterosis in three-way hybrids and found that one out of 12 three-way crosses studied showed significant high-parent heterosis. Three-way hybrids showed less heterosis than single crosses, as expected on genetic grounds.

CHAPTER III
MATERIALS AND METHODS

Three groups of trials were designed between 1990 and 1993 in the U.S.A., Texas and in Kenya. The first group consisted of three different sets in 1990, for preliminary evaluation at College Station (subset 1, subset 2, and main set). A second group of trials was in Texas during 1991 and 1992, and was replicated at four locations (College Station, Halfway, Corpus Christi and Chillicothe) in two years. Materials for these Texas trials were selected from the 1990 preliminary trials at College Station. The last group of trials were in Kenya in 1992/3 at four locations, one of which had two seasons of evaluation giving a total of five locations. The entries for the trials in the U.S.A. overlapped but those in Kenya involved parental lines from the Texas A&M program and cultivars from the Kenya sorghum breeding program. The materials from the Texas A&M University program were provided by Dr. F.R. Miller, who also assisted in making the crosses. Some of the crosses of the trials in Kenya were made at the National Range Research Centre, Kiboko in Kenya with the assistance of Dr. Lynn Gourley. The male sterile (A) lines, maintainer (B) lines and fertility-restoring (R) lines were selected for trials to produce hybrids, so that hand emasculation was not a necessary procedure in the production of the hybrids. For the trials in Texas, two sterility systems (A_1 and A_2) were utilized. In all the trials, B-lines (fertile non-restorer counterparts of each male sterile) were included in the experiments in lieu of the A-lines with the assumption that the two were isogenic and differing only in their cytoplasms. Sorghum is a self-pollinated plant, and therefore the parents in the studies were considered highly inbred.

Preliminary Evaluations at College Station, Texas in 1990

Three sets of trials were conducted in 1990 at the Texas A&M Research Farm, College Station. The sets of trials were coded subset 1, subset 2, and main set; each with differing number of entries. Subset 1 had a total of 34 entries; seven lines (four B-lines and three R-lines), nine single crosses (eight fertile and one sterile), 11 three-way crosses (four with sterile F_1 and seven with A-line as female parent), and seven double crosses (Table 1). Entries for subset 2 included six parental lines (three B_2-lines and three R-lines), three single crosses (two fertile and one sterile), four three-way crosses (two with R-line and two with B_2-line as male parent) and four double crosses, a total of 17 entries (Table 2). Main set consisted of 142 entries; 14 parental lines (seven each of B-lines and R-lines), 34 single crosses (32 fertile and eight sterile), 54 three-way crosses (22 with A-line and 32 with sterile F_1 as female parent), and 40 double crosses (Table 3).

Table 1. Entries for subset 1 at College Station in 1990.

Entry	Cultivar	Type
1	B_2Tx632	Parental line A_2 cytoplasm
2	BTx631	Parental line A_1 cytoplasm
3	B_2Tx636	Parental line A_2 cytoplasm
4	B_2Tx637	Parental line A_2 cytoplasm
5	RTx432	Parental restorer line, A_1, and A_2
6	SC599-11E	Parental restorer line , A_1, and A_2
7	SC103-12E	Parental restorer line, A_1, and A_2
8	ATx631*RTx432	Fertile single-cross hybrid
9	ATx631*SC599-11E	Fertile single-cross hybrid
10	ATx631*B_2Tx636	Fertile single-cross hybrid
11	ATx631*B_2Tx637	Fertile single-cross hybrid
12	ATx631*SC103-12E	Fertile single-cross hybrid
13	A_2Tx632*RTx432	Fertile single-cross hybrid
14	A_2Tx632*SC599-11E	Fertile single-cross hybrid
15	A_2Tx632*SC103-12E	Fertile single-cross hybrid
16	A_2Tx632*BTx631	Sterile single-cross hybrid
17	(A_2Tx632*BTx631)*RTx432	Fertile three-way-cross F_1 female R-line male
18	(A_2Tx632*BTx631)*SC599-11E	Fertile three-way-cross F_1 female R-line male
19	(A_2 Tx632*BTx631)*B_2Tx636	Sterile three-way-cross F_1 female B_2-line male
20	(A_2Tx632*BTx631)*B_2Tx637	Sterile three-way-cross F_1 female B_2-line male
21	ATx631*(A_2Tx632*RTx432)	Fertile three-way-cross F_1 male
22	ATx631*(A_2Tx632*SC599-11E)	Fertile three-way-cross F_1 male
23	ATx631*(A_2Tx636*RTx432)	Fertile three-way-cross F_1 male
24	ATx631*(A_2Tx636*SC599-11E)	Fertile three-way-cross F_1 male
25	ATx631*(A_2Tx637*RTx432)	Fertile three-way-cross F_1 male
26	ATx631*(A_2Tx637*SC599-11E)	Fertile three-way-cross F_1 male
27	ATx631*(A_2Tx636*SC103-12E)	Fertile three-way-cross F_1 male
28	(A_2Tx632*BTx631)*(A_2Tx632*RTx432)	Fertile double-cross hybrid
29	(A_2Tx632*BTx631)*(A_2Tx632*SC599-11E)	Fertile double-cross hybrid
30	(A_2Tx632*BTx631)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
31	(A_2Tx632*BTx631)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
32	(A_2Tx632*BTx631)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
33	(A_2Tx632*BTx631)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
34	(A_2Tx632*BTx631)*(A_2Tx636*SC103-12E)	Fertile double-cross hybrid

Table 2. Entries for subset 2 at College Station in 1990.

Entry	Cultivar	Type
1	B_2Tx636	Parental line A_2 cytoplasm
2	B_2Tx637	Parental line A_2 cytoplasm
3	B_2Tx632	Parental line A_2 cytoplasm
4	RTx430	Parental restorer in A_1, maintainer in A_2
5	RTx432	Parental restorer line in A_1 and A_2
6	SC599-11E	Parental restorer line in A_1 and A_2
7	A_2Tx632*RTx432	Fertile single-cross hybrid
8	A_2Tx632*SC599-11E	Fertile single-cross hybrid
9	A_2Tx632*RTx430	Sterile single-cross hybrid
10	(A_2Tx632*RTx430)*RTx432	Fertile three-way-cross R-line male
11	(A_2Tx632*RTx430)*SC599-11E	Fertile three-way-cross R-line male
12	(A_2Tx632*RTx430)*B_2Tx636	Sterile three-way-cross B_2-line male
13	(A_2Tx632*RTx430)*B_2Tx637	Sterile three-way-cross B_2-line male
14	(A_2Tx632*RTx430)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
15	(A_2Tx632*RTx430)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
16	(A_2Tx632*RTx430)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
17	(A_2Tx632*RTx430)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid

Table 3. Entries for main set at College Station in 1990.

Entry	Cultivar	Type
1	BTx631	Parental line A_1 cytoplasm
2	BTx630	Parental line A_1 cytoplasm
3	B8106	Parental line A_1 cytoplasm
4	BTx629	Parental line A_1 cytoplasm
5	B_2Tx632	Parental line A_2 cytoplasm
6	B_2Tx636	Parental line A_2 cytoplasm
7	B_2Tx637	Parental line A_2 cytoplasm
8	RTx432	Parental restorer line, A_1 and A_2
9	SC599-11E	Parental restorer line, A_1 and A_2
10	SC103-12E	Parental restorer line, A_1 and A_2
11	RTx435	Parental restorer line, A_1
12	RTAM428	Parental restorer line, A_1
13	RTx2737	Parental restorer line, A_1
14	RTx430	Parental restorer line, A_1
15	ATx630*RTx432	Fertile single-cross hybrid
16	ATx630*SC599-11E	Fertile single-cross hybrid
17	ATx630*SC103-12E	Fertile single-cross hybrid
18	ATx630*B_2Tx636	Fertile single-cross hybrid
19	ATx630*B_2Tx637	Fertile single-cross hybrid
20	ATx631*RTx432	Fertile single-cross hybrid
21	ATx631*SC599-11E	Fertile single-cross hybrid
22	ATx631*SC103-12E	Fertile single-cross hybrid
23	ATx631*B_2Tx636	Fertile single-cross hybrid
24	ATx631*B_2Tx637	Fertile single-cross hybrid
25	ATx629*RTx432	Fertile single-cross hybrid
26	ATx629*SC599-11E	Fertile single-cross hybrid
27	ATx629*B_2Tx636	Fertile single-cross hybrid
28	ATx629*B_2Tx637	Fertile single-cross hybrid
29	A8106*RTx432	Fertile single-cross hybrid
30	A8106*B_2Tx636	Fertile single-cross hybrid
31	A8106*B_2Tx637	Fertile single-cross hybrid
32	A_2Tx632*RTx432	Fertile single-cross hybrid
33	A_2Tx632*SC599-11E	Fertile single-cross hybrid
34	A_2Tx632*SC103-12E	Fertile single-cross hybrid
35	A_2Tx636*RTx432	Fertile single-cross hybrid
36	A_2Tx636*SC599-11E	Fertile single-cross hybrid
37	A_2Tx636*SC103-12E	Fertile single-cross hybrid
38	A_2Tx637*RTx432	Fertile single-cross hybrid
39	A_2Tx637*SC599-11E	Fertile single-cross hybrid
40	A_2Tx637*SC103-12E	Fertile single-cross hybrid
41	A_2Tx632*BTx629	Sterile single-cross hybrid
42	A_2Tx632*BTx630	Sterile single-cross hybrid
43	A_2Tx632*BTx631	Sterile single-cross hybrid
44	A_2Tx632*B8106	Sterile single-cross hybrid
45	A_2Tx632*RTx430	Sterile single-cross hybrid
46	A_2Tx632*RTx435	Sterile single-cross hybrid
47	A_2Tx632*RTAM428	Sterile single-cross hybrid
48	A_2Tx632*RTx2737	Sterile single-cross hybrid

Table 3. Continued.

Entry	Cultivar	Type
49	ATx630*(A_2Tx632*RTx432)	Fertile three-way-cross, line as female
50	ATx630*(A_2Tx632*SC599-11E)	Fertile three-way-cross, line as female
51	ATx630*(A_2Tx636*RTx432)	Fertile three-way-cross, line as female
52	ATx630*(A_2Tx636*SC599-11E)	Fertile three-way-cross , line as female
53	ATx630*(A_2Tx636*SC103-12E)	Fertile three-way-cross, line as female
54	ATx630*(A_2Tx637*RTx432)	Fertile three-way-cross, line as female
55	ATx630*(A_2Tx637*SC599-11E)	Fertile three-way-cross, line as female
56	ATx631*(A_2Tx632*RTx432)	Fertile three-way-cross, line as female
57	ATx631*(A_2Tx632*SC599-11E)	Fertile three-way-cross, line as female
58	ATx631*(A_2Tx636*RTx432)	Fertile three-way-cross, line as female
59	ATx631*(A_2Tx636*SC599-11E)	Fertile three-way-cross, line as female
60	ATx631*(A_2Tx636*SC103-12E)	Fertile three-way-cross, line as female
61	ATx631*(A_2Tx637*RTx432)	Fertile three-way-cross, line as female
62	ATx631*(A_2Tx637*SC599-11E)	Fertile three-way-cross, line as female
63	ATx629*(A_2Tx636*RTx432)	Fertile three-way-cross, line as female
64	ATx629*(A_2Tx636*SC599-11E)	Fertile three-way-cross, line as female
65	ATx629*(A_2Tx637*RTx432)	Fertile three-way-cross, line as female
66	ATx629*(A_2Tx637*SC599-11E)	Fertile three-way-cross, line as female
67	A8106*(A_2Tx636*RTx432)	Fertile three-way-cross, line as female
68	A8106*(A_2Tx636*SC599-11E)	Fertile three-way-cross, line as female
69	A8106*(A_2Tx637*RTx432)	Fertile three-way-cross, line as female
70	A8106*(A_2Tx637*SC599-11E)	Fertile three-way-cross, line as female
71	A_2Tx632*(A_2Tx632*RTx432)	Fertile three-way-cross, line as female
72	A_2Tx632*(A_2Tx632*SC599-11E)	Fertile three-way-cross, line as female
73	A_2Tx632*(A_2Tx636*SC103-12E)	Fertile three-way-cross, line as female
74	(A_2Tx632*BTx630)*RTx432	Fertile three-way-cross, R-line as male
75	(A_2Tx632*BTx630)*SC599-11E	Fertile three-way-cross, R-line as male
76	(A_2Tx632*BTx630)*B_2Tx636	Sterile three-way-cross, B_2-line as male
77	(A_2Tx632*BTx630)*B_2Tx637	Sterile three-way-cross, B_2-line as male
78	(A_2Tx632*BTx631)*RTx432	Fertile three-way-cross, R-line as male
79	(A_2Tx632*BTx631)*SC599-11E	Fertile three-way-cross, R-line as male
80	(A_2Tx632*BTx631)*B_2Tx636	Sterile three-way-cross, B_2-line as male
81	(A_2Tx632*BTx631)*B_2Tx637	Sterile three-way-cross, B_2-line as male
82	(A_2Tx632*BTx629)*RTx432	Fertile three-way-cross, R-line as male
83	(A_2Tx632*BTx629)*SC599-11E	Fertile three-way-cross, R-line as male
84	(A_2Tx632*B8106)*RTx432	Fertile three-way-cross, R-line as male
85	(A_2Tx632*B8106)*SC599-11E	Fertile three-way-cross, R-line as male
86	(A_2Tx632*B8106)*B_2Tx636	Sterile three-way-cross, B_2-line as male
87	(A_2Tx632*B8106)*B_2Tx637	Sterile three-way-cross, B_2-line as male
88	(A_2Tx632*RTx430)*RTx432	Fertile three-way-cross, R-line as male
89	(A_2Tx632*RTx430)*SC599-11E	Fertile three-way-cross, R-line as male
90	(A_2Tx632*RTx430)*B_2Tx636	Sterile three-way-cross, B_2-line as male
91	(A_2Tx632*RTx430)*B_2Tx637	Sterile three-way-cross, B_2-line as male
92	(A_2Tx632*RTx435)*RTx435	Sterile three-way-cross, R-line as male
93	(A_2Tx632*RTx435)*SC599-11E	Fertile three-way-cross, R-line as male
94	(A_2Tx632*RTx435)*B_2Tx636	Sterile three-way-cross, B_2-line as male
95	(A_2Tx632*RTx435)*B_2Tx637	Sterile three-way-cross, B_2-line as male

Table 3. Continued.

Entry	Cultivar	Type
96	(A_2Tx632*RTAM428)*RTx432	Fertile three-way-cross, R-line as male
97	(A_2Tx632*RTAM428)*SC599-11E	Fertile three-way-cross, R-line as male
98	(A_2Tx632*RTAM428)*B_2Tx636	Sterile three-way-cross, B_2-line as male
99	(A_2Tx632*RTAM428)*B_2Tx637	Sterile three-way-cross, B_2-line as male
100	(A_2Tx632*RTx2737)*RTx432	Sterile three-way-cross, R-line as male
101	(A_2Tx632*RTx2737)*SC599-11E	Fertile three-way-cross, R-line as male
102	(A_2Tx632*RTx2737)*B_2Tx636	Sterile three-way-cross, B_2-line as male
103	(ATx631*BTx630)*(A_2Tx632*RTx432)	Fertile double-cross hybrid
104	(ATx631*BTx630)*(A_2Tx632*SC599-11E)	Fertile double-cross hybrid
105	(ATx631*BTx630)*(A_2Tx636*SC103-12E)	Fertile double-cross hybrid
106	(A_2Tx632*BTx630)*(A_2Tx632*RTx432)	Fertile double-cross hybrid
107	(A_2Tx632*BTx630)*(A_2Tx632*SC599-11E)	Fertile double-cross hybrid
108	(A_2Tx632*BTx630)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
109	(A_2Tx632*BTx630)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
110	(A_2Tx632*BTx630)*(A_2Tx636*SC103-12E)	Fertile double-cross hybrid
111	(A_2Tx632*BTx630)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
112	(A_2Tx632*BTx630)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
113	(A_2Tx632*BTx631)*(A_2Tx632*RTx432)	Fertile double-cross hybrid
114	(A_2Tx632*BTx631)*(A_2Tx632*SC599-11E)	Fertile double-cross hybrid
115	(A_2Tx632*BTx631)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
116	(A_2Tx632*BTx631)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
117	(A_2Tx632*BTx631)*(A_2Tx636*SC103-12E)	Fertile double-cross hybrid
118	(A_2Tx632*BTx631)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
119	(A_2Tx632*BTx631)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
120	(A_2Tx632*BTx629)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
121	(A_2Tx632*BTx629)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
122	(A_2Tx632*BTx629)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
123	(A_2Tx632*BTx629)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
124	(A_2Tx632*B8106)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
125	(A_2Tx632*B8106)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
126	(A_2Tx632*B8106)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
127	(A_2Tx632*B8106)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
128	(A_2Tx632*RTx430)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
129	(A_2Tx632*RTx430)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
130	(A_2Tx632*RTx430)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
131	(A_2Tx632*RTx430)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
132	(A_2Tx632*RTx435)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
133	(A_2Tx632*RTx435)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
134	(A_2Tx632*RTx435)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
135	(A_2Tx632*RTx435)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
136	(A_2Tx632*RTAM428)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
137	(A_2Tx632*RTAM428)*(A_2Tx636*SC599-11E)	Fertile double-cross hybrid
138	(A_2Tx632*RTAM428)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
139	(A_2Tx632*RTAM428)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid
140	(A_2Tx632*RTx2737)*(A_2Tx636*RTx432)	Fertile double-cross hybrid
141	(A_2Tx632*RTx2737)*(A_2Tx637*RTx432)	Fertile double-cross hybrid
142	(A_2Tx632*RTx2737)*(A_2Tx637*SC599-11E)	Fertile double-cross hybrid

The three sets of trials for preliminary evaluation were planted on April 3, 1990. The parental B-lines and R-lines, single, three-way, and double cross hybrids were arranged in randomized complete-block designs with 3 replicates. Single-row plots 1 m apart and 5 m in length were machine planted under a recommended fertilization regime for the area and later thinned to a population equivalent to 100,000 plants per hectare. Measurements were recorded on per plot basis for the following characters:

1 Days to 50% anthesis: days from planting to date when 50% of main-culm panicles in a plot had anthers dehiscing halfway down the panicle.

2 Plant height: distance (cm) from soil level to tip of main-culm panicle at maturity, measured on 5 random plants per plot for parental lines and single crosses, and 10 random plants for three-way and double crosses.

3 Panicle exsertion: distance (cm) from the flag leaf ligule to the base of the panicle. Same plants measured as for plant height.

4 Panicle length: length (cm) from the lowest panicle branch to the tip of the panicle. Same plants measured as for plant height and panicle exsertion.

5 Panicle weight: weight (g) at 13% moisture of panicles harvested (before threshing) per plot. For calculation of threshing percentage only and not for reporting.

6 Grain yield: weight (g) at 13% moisture of threshed grain per plot. Converted by appropriate factor to kg/ha.

7 Threshing percentage (%): calculated as the ratio of grain yield (g) to panicle weight (g) as a percentage.

8 1000-seed weight: weight (g) of 1000 seeds counted by an electronic seed counter.

9 Test weight: weight (g) of 500 ml of grain, converted by appropriate factor to kg/ha.

The character 1000-seed weight was not recorded for main set.

Harvesting was done when full panicle maturity was reached. Panicles harvested from each plot were dried artificially to a grain moisture content of approximately 13% before threshing, and grain weights were recorded on this basis.

Statistical Procedures

The conventional analyses of variance were performed for each trait using individual plot observations to determine differences among cultivars. For plant height, panicle exsertion, and panicle length, plot means from each plot were used in the analysis of variance. Within-plot standard deviations were calculated for each cultivar type for the three characters and were used as a measure of variability for each type.

The following statistical model was applied:

$$Y_{ij} = \mu + R_i + G_j + \varepsilon_{ij}$$

Where, Y_{ij} = observation of the jth cultivar (G) in the ith replicate (R);

μ = overall mean

ε_{ij} = residual error.

The cultivar effects were partitioned into types of parents (P), and single cross (SC), three-way cross (TWC), and double cross (DC) hybrids (H). The different types were compared by useful single-degree-of-freedom orthogonal contrasts. When measured traits had indicated significant differences ($P \leq 0.05$) in the analysis of variance mean, separations among the cultivars were done with a Fisher's protected least significant difference (LSD) test ($P \leq 0.05$).

Trials in Texas in 1991 and 1992

The materials selected for evaluation in this study included eight parental lines (two each of B_1-lines and B_2-lines, and four R-lines), 19 single-crosses (two sterile and 17 fertile), 15 three-way crosses (seven with sterile parental line and eight with sterile F_1 as female parents) and 10 double crosses. The entries (Table 4) were planted at each of the four locations in Texas; College Station, Halfway, Corpus Christi, and Chillicothe in two years, 1991 and 1992, in randomized complete-block designs. Three replicates were used in all the trials.

The experiments at College Station were planted on April 1, 1991 and March 25, 1992. At Halfway, planting dates were May 28, 1991 and June 5, 1992. Planting dates at Corpus Christi were on March 4, 1991 and March 6 1992. Trials at Chillicothe were planted on July 18, 1991 and July 7, 1992.

Single-row plots 1 m apart and 5 m long were used for College Station, Corpus Christi and Chillicothe, while plots at Halfway were single-row plots 4.87 m long and 102 cm apart. At all the locations, thinning of the crop was done to a population of between 85,000 to 100,000 plants per hectare. Differences in planting dates, interrow spacings, fertilizer applications (recommended regimes for each specific area), inherent soil fertility, and climatic conditions provided a good range in productivity among the experimental location-year combinations.

Measurements were made on the following traits using similar procedures as described for the preliminary evaluation trials at College Station for 1990:

Days to 50% anthesis, plant height, panicle exsertion, grain yield, and 1000-seed weight.

Table 4. Entries for evaluation at four locations in Texas in 1991 and 1992.

Entry	Cultivar	Type
1	BTx630	Parental line A_1 cytoplasm
2	BTx631	Parental line A_1 cytoplasm
3	B_2Tx632	Parental line A_2 cytoplasm
4	$B_2$8602	Parental line A_2 cytoplasm
5	RTx430	Parental restorer line in A_1
6	RTx432	Parental restorer line in A_1 and A_2
7	SC103-12E	Parental restorer line in A_1 and A_2
8	SC599-11E	Parental restorer line in A_1 and A_2
9	ATx630*BTx631	Sterile single-cross hybrid
10	ATx630*B_2Tx632	Fertile single-cross hybrid
11	ATx630*$B_2$8602	Fertile single-cross hybrid
12	ATx630*RTx432	Fertile single-cross hybrid
13	ATx630*SC103-12E	Fertile single-cross hybrid
14	ATx630*SC599-11E	Fertile single-cross hybrid
15	ATx631*B_2Tx632	Fertile single-cross hybrid
16	ATx631*$B_2$8602	Fertile single-cross hybrid
17	ATx631*RTx430	Fertile single-cross hybrid
18	ATx631*RTx432	Fertile single-cross hybrid
19	ATx631*SC103-12E	Fertile single-cross hybrid
20	ATx631*SC599-11E	Fertile single-cross hybrid
21	A_2Tx632*RTx430	Sterile single-cross hybrid
22	A_2Tx632*RTx432	Fertile single-cross hybrid
23	A_2Tx632*SC103-12E	Fertile single-cross hybrid
24	A_2Tx632*SC599-11E	Fertile single-cross hybrid
25	$A_2$8602*RTx432	Fertile single-cross hybrid
26	$A_2$8602*SC103-12E	Fertile single-cross hybrid

Table 4. Continued.

Entry	Cultivar	Type
27	$A_2$8602*SC599-11E	Fertile single-cross hybrid
28	(A_2Tx632*BTx630)*RTx432	Fertile three-way-cross F_1 female R-line male
29	(A_2Tx632*BTx630)*SC103-12E	Fertile three-way-cross F_1 female R-line male
30	(A_2Tx632*BTx630)*SC599-11E	Fertile three-way-cross F_1 female R-line male
31	ATx630*($A_2$8602*RTx432)	Fertile three-way-cross line female F_1 male
32	ATx630*($A_2$8602*SC103-12E)	Fertile three-way-cross line female F_1 male
33	ATx630*($A_2$8602*SC599-12E)	Fertile three-way-cross line female F_1 male
34	ATx631*(A_2Tx632*RTx432)	Fertile three-way-cross line female F_1 male
35	ATx631*(A_2Tx632*SC599-11E)	Fertile three-way-cross line female F_1 male
36	ATx631*(A_2Tx632*SC103-12E)	Fertile three-way-cross line female F_1 male
37	ATx631*($A_2$8602*RTx432)	Fertile three-way-cross line female F_1 male
38	A_2Tx632*($A_2$8602*SC103-12E)	Fertile three-way-cross line female F_1 male
39	(ATx631*BTx630)*RTx432	Fertile three-way-cross F_1 female R-line male
40	(ATx631*BTx630)*SC599-11E	Fertile three-way-cross F_1 female R-line male
41	(A_2Tx632*RTx430)*SC103-12E	Fertile three-way-cross F_1 female R-line male
42	(A_2Tx632*RTx430)*SC599-11E)	Fertile three-way-cross F_1 female R-line male
43	(ATx631*BTx630)*(A_2Tx632*RTx432)	Fertile double-cross hybrid
44	(ATx631*BTx630)*(A_2Tx632*SC103-12E)	Fertile double-cross hybrid
45	(ATx631*BTx630)*(A_2Tx632*SC599-11E)	Fertile double-cross hybrid
46	(ATx631*BTx630)*($A_2$8602*SC103-12E)	Fertile double-cross hybrid
47	(A_2Tx632*BTx630)*($A_2$8602*RTx432)	Fertile double-cross hybrid
48	(A_2Tx632*BTx630)*($A_2$8602*SC599-11E)	Fertile double-cross hybrid
49	(A_2Tx632*BTx630)*($A_2$8602*SC103-12E)	Fertile double-cross hybrid
50	(A_2Tx632*BTx631)*($A_2$8602*RTx432)	Fertile double-cross hybrid
51	(A_2Tx632*BTx631)*($A_2$8602*SC599-11E)	Fertile double-cross hybrid
52	(A_2Tx632*BTx630)*($A_2$8602*SC103-12E)	Fertile double-cross hybrid

Statistical Procedures

The analyses of variance for each character at each location-year combination were performed for individual environments following a model similar to that described for the preliminary evaluation trials of 1990 at College Station. Bartletts' test as described by Snedecor and Cochran (1967) was used to assess homogeneity of variances prior to combined analyses.

In the combine analysis environments (combinations of locations and years) and replications were considered random effects, while cultivars (hybrids and lines) were considered fixed effects (McIntosh, 1983). The statistical model used in the combined analysis was as follows:

$$Y_{ijk} = \mu + E_i + R_{j(i)} + G_k + GE_{ik} + \varepsilon_{ijk}$$

where, Y_{ijk} = observation of the kth cultivar (G) in the jth replicate (R) within the ith environment (E); μ = grand mean ; E_i = the effect of the ith environment; $R_{j(i)}$ = effect of the jth replication within the ith environment; G_k = effect of the kth cultivar; GE_{ik} = interaction of the ith environment with the kth cultivar; and ε_{ijk} = the random error term.

The sum of squares attributable to entries was partitioned into orthogonal comparisons among types and among entries within types. The entry X environment sums of squares were similarly subdivided into the interactions of environments with individual comparisons (similar to Jowett, 1972). Where the entry X environment variance was significant, the data were subjected to stability analysis using the method of Eberhart and Russell (1966). Mean squares among types and among entries within a type were tested for significance by the F-ratio, using the pooled entry X environment interaction mean square as the denominator.

The regression model $Y_{ij} = \mu + \beta_i I_j + \Upsilon_{ij}$ (Eberhart and Russell, 1966) was used for the analysis of the responses of the entries to the different environments (stability analysis), where, Y_{ij} = the mean of the ith cultivar in the jth environment; μ= the mean over all cultivars and environments; β_i = the regression coefficient (slope) of performance of the ith cultivar on the environmental index; I_j = environmental index of the jth environment; and Υ_{ij} = random deviates from regression.

An environmental index was calculated for each environment by subtracting the grand mean of all experiments from the mean of all cultivars in each environment. The stability parameters (b_i) and the deviation from regression of cultivar means over environmental index were computed by regressing each entry in each environment upon the environmental index. This analysis permitted the partitioning of environment and entry X environment interaction sources of variation into environment (linear), entry X environment (linear) interaction [sum of squares due to regression, (b_i)], and unexplainable deviation from linear regression (pooled deviation mean square, S^2_{di}). The entry X environment (linear) sums of squares and the pooled deviations sums of squares were further partitioned into components representing comparisons within and among types. Significance of entry X environment (linear) mean square was tested using deviation mean square as denominator. To test for significance of deviation mean squares, the average pooled error mean square from combined analysis of variance was used as a denominator in the F-test.

The average regression coefficients for each trait studied was 1.0. The statistic b is a measure of the average increase in yield of a cultivar per unit of increase in the environmental index. Regression coefficients greater than 1.0 indicated ability to respond to favorable growing conditions, whereas those less than 1.0 indicated lack of ability to respond to favorable growing conditions. The statistic S^2_d measures how well the predicted response agrees with the observed response and includes cultivar X environment interactions. Small nonsignificant deviation mean squares indicated linear responses to environments with no specific interactions. Significant deviation mean squares indicated nonlinear response or specific interactions with environments.

Trials in Kenya during 1992/93

The male sterile (A) lines, maintainer (B) lines, and fertility restoring (R) lines selected to produce the hybrids evaluated in these studies were:

A and B lines	R-lines
A/BTx630	RTx432
A/BTx631	SC599-11E
A/BTx3197	Lulu D
A/BTx635	Serena

Each A-line was crossed with each B-line other than its counterpart to synthesize six possible (excluding reciprocals) sterile parental single crosses (A_i X $B_{i'}$). These sterile single crosses were then crossed to each of the four R-lines to produce seed of 24 possible three-way crosses [(A_i X $B_{i'}$) X R_j]. 16 fertile single crosses (A_i X R_j) also were produced by crossing each of the A-lines with each R-line. The lines used have all been utilized in breeding programs either in Kenya, at Texas A&M University or in other sorghum breeding programs worldwide. Each of the four B-lines and R-lines, six male-sterile single crosses, 16 fertile single crosses and the 24 fertile three-way hybrids were included in the experiments, for a total of 54 entries (Table 5).

The experiments were conducted in 1992, during the long rainy season (March-June) at the National Fibre Research Centre at Kibos, National Range Research Centre at Kiboko, and Agricultural Research Sub-centre at Alupe. At the Western Regional Research Centre at

Table 5. Entries for evaluation at five locations in Kenya during 1992/93.

Entry	Cultivar	Type
1	BTx630	Parental maintainer line
2	BTx631	Parental maintainer line
3	BTx3197	Parental maintainer line
4	BTx635	Parental maintainer line
5	Serena	Restorer cultivar
6	Lulu D	Restorer cultivar
7	RTx432	Parental restorer line
8	SC599-11E	Parental restorer line
9	ATx631*BTx630	Sterile F_1 hybrid
10	ATx3197*BTx630	Sterile F_1 hybrid
11	ATx3197*BTx631	Sterile F_1 hybrid
12	ATx635*BTx3197	Sterile F_1 hybrid
13	A.GV1*BTx630	Sterile F_1 hybrid
14	A.GV1*BTx631	Sterile F_1 hybrid
15	ATx630*Serena	Fertile F_1 hybrid
16	ATx630*Lulu D	Fertile F_1 hybrid
17	ATx630*RTx432	Fertile F_1 hybrid
18	ATx630*SC599-11E	Fertile F_1 hybrid
19	ATx631*Serena	Fertile F_1 hybrid
20	ATx631*Lulu D	Fertile F_1 hybrid
21	ATx631*RTx432	Fertile F_1 hybrid
22	ATx631*SC599-11E	Fertile F_1 hybrid
23	ATx3197*Serena	Fertile F_1 hybrid
24	ATx3197*Lulu D	Fertile F_1 hybrid
25	ATx3197*RTx432	Fertile F_1 hybrid
26	ATx3197A*SC599-11E	Fertile F_1 hybrid
27	ATx635*Serena	Fertile F_1 hybrid

Table 5. Continued.

Entry	Cultivar	Type
28	ATx635*LULUD	Fertile F_1 hybrid
29	ATx635*RTx432	Fertile F_1 hybrid
30	ATx635*SC599-11E	Fertile F_1 hybrid
31	(ATx631*BTx630)*Serena	Fertile three-way-cross hybrid
32	(ATx631*BTx630)*Lulu D	Fertile three-way-cross hybrid
33	(ATx631*BTx630)*RTx432	Fertile three-way-cross hybrid
34	(ATx631*BTx630)*SC599-11E	Fertile three-way-cross hybrid
35	(ATx3197*BTx630)*Serena	Fertile three-way-cross hybrid
36	(ATx3197*BTx630)*Lulu D	Fertile three-way-cross hybrid
37	(ATx3197*BTx630)*RTx432	Fertile three-way-cross hybrid
38	(ATx3197*BTx630)*SC599-11E	Fertile three-way-cross hybrid
39	(ATx635*BTx630)*Serena	Fertile three-way-cross hybrid
40	(ATx635*BTx630)*Lulu D	Fertile three-way-cross hybrid
41	(ATx635*BTx630)*RTx432	Fertile three-way-cross hybrid
42	(ATx3197*BTx630)*SC599-11E	Fertile three-way-cross hybrid
43	(ATx3197*BTx631)*Serena	Fertile three-way-cross hybrid
44	(ATx3197*BTx631)*Lulu D	Fertile three-way-cross hybrid
45	(ATx3197*BTx631)*RTx432	Fertile three-way-cross hybrid
46	(ATx3197*BTx631)*SC599-11E	Fertile three-way-cross hybrid
47	(ATx635*BTx631)*Serena	Fertile three-way-cross hybrid
48	(ATx635*BTx631)*Lulu D	Fertile three-way-cross hybrid
49	(ATx635*BTx631)*RTx432	Fertile three-way-cross hybrid
50	(ATx635*BTx631)*SC599-11E	Fertile three-way-cross hybrid
51	(ATx635*BTx3197)*Serena	Fertile three-way-cross hybrid
52	(ATx635*BTx3197)*Lulu D	Fertile three-way-cross hybrid
53	(ATx635*BTx3197)*RTx432	Fertile three-way-cross hybrid
54	(ATx635*BTx3197)*SC599-11E	Fertile three-way-cross hybrid

Kakamega, two seasons were utilized, the long and short (October-December) seasons. These locations, except Kiboko, have a bimodal rainfall pattern with peaks in March/May and October/November. Kiboko has a unimodal rainfall pattern with a peak in October/November. The conditions at Kiboko were dryland and minimal irrigation was necessary for crop establishment and at flowering. The long rainy season at Kakamega was extremely wet, while the short season had moderate rainfall as did Kibos and Alupe. The trials were considered as five different environments for the combine analysis.

Seeds for all the 54 cultivars were hand sown at the locations on different planting dates: April 1, 1992 at Kibos; April 9 at Kakamega (long season); April 17 at Alupe; May 7 at Kiboko; and October 12 at Kakamega (short season). Randomized complete-block designs with three replications were employed in each environment. Plots were single-rows 5 m in length and 0.6 m between rows, with four guard rows at the both ends of each block. Plants within a row were spaced at 15 cm with a total plant population of about 114,000 plants/hectare. Cultural practices were those recommended for sorghum production in the respective areas.

Data were obtained for days to 50% anthesis, plant height, panicle exsertion and panicle length at the five environments; 1000-seed weight (g) based on 100-seed sample at Kibos and Kakamega (both seasons), whereas panicle weight, grain yield, and threshing percentage were recorded for all environments except Alupe. The crop at Alupe was harvested but could not be threshed and weights recorded. The harvesting was done in the rain, and the seeds sprouted on the panicles in storage. The procedures described for preliminary evaluation trials at College Station in 1990 were adopted in the collection of data except for 1000-seed weight; the sample of 100 seeds were manually counted in these experiments.

Statistical Procedures

The model described for the preliminary evaluation at College Station, 1990 was adopted for the analysis of variance at individual environments. Similarly, the combined analysis of variance over all the environments and the stability analysis were performed for these experiments following the models described in the Texas trials of 1991 and 1992.

Genetic Effects, Prediction of Yield, and Heterosis

The relative magnitude of the different types of effects present in the fixed set of cultivars was investigated by means of a genetic analysis according to a general fixed model suggested by Gardner and Eberhart (1966), and Eberhart and Gardner (1966). Information from parental lines, parental and non-parental single crosses, and three-way crosses was used to assess effects in terms of which the generation means were expressed as follows:

B-lines	$Y_i = \mu + a_i$
R-lines	$Y_j = \mu + a_j$
SSC's	$Y_{ii'} = \mu + ½(a_i + a_{i'}) + \bar{h} + h_i + h_{i'} + s_{ii'}$
FSC's	$Y_{ij} = \mu + ½(a_i + a_j) + \bar{h} + h_i + h_j + s_{ij}$
TWC's	$Y_{ii'j} = \mu + ¼(a_i + a_{i'}) + ½a_j + \bar{h} + ½(h_i + h_{i'}) + h_j + ½(s_{ij} + s_{i'j})$

where,

SSC, FSC, and TWC = male-sterile single crosses, fertile single crosses and three-way crosses, respectively

μ = the mean of all parental lines

a_i and $a_{i'}$ = additive gene effect due to the line i (A or B-line)

a_j = additive gene effect due to line j (R-line)

$\bar{h}$ = average heterosis of the single crosses

h_i = heterosis specific to line i (line heterosis) in A X B crosses

h_j = heterosis specific to line j (line heterosis)

$s_{ii'}$ = the specific heterosis that occurs when the A-line is mated to B-line (ii' cross)

s_{ij} = the specific heterosis that occurs when the A-line is mated to R-line (ij cross)

The restrictions imposed to estimate the parameters are,

$$\sum a = \sum h = \sum_{i}\sum_{i'}{}_{i \neq i'} s_{ii'} = \sum_{i} s_{ij} = \sum_{j}{}_{ij} = 0$$

The least-squares procedure was used to partition entry sum of squares into variations due to various genetic effects with the genetic model described by using the entry means data in each environment and for over all environments as the dependent (Y) variates. Because the parameters were not orthogonal, they were fitted sequentially in the following order:

1. μ, a
2. μ, a, $\bar{h}$
3. μ, a, $\bar{h}$, h
4 μ, a, $\bar{h}$, h, s

Estimates of the effects also were obtained with the least-squares procedures. Tests of significance of the genetic effects were made with an F-test by using the pooled deviation mean squares as the denominator, whereas the experimental error was used to test the significance of the deviations from the full model. For all analyses, the entries were considered fixed and environments assumed random.

Grain yield prediction of the three-way cross hybrids were predicted for each environment and over all environments by several methods.

Method 1. The effects, described in the model, were estimated with the least squares procedure from the parental, fertile single cross, and sterile single cross data only. Only the significant effects were used to predict the performance of three-way cross.

Method 2. Non-parental single-cross (A_i X R_j) data were used to estimate general and specific effects according to the factorial mating design. These effects were then used to predict the three-way cross yield as:

$$\hat{Y}_{(Ai \times Bi') \times Rj} = \mu + ½(g_i + g_{i'}) + g_j + ½(s_{ij} + s_{i'j'})$$

where g and s represent the general and specific effects, respectively.

This predictor is analogous to Method B by Jenkins (1934) for predicting the yield of double cross. Yield of the three-way hybrid is done by averaging the two non-parental single crosses, i.e.

$$\hat{Y}_{(Ai \times Bi') \times Rj} = ½[(A_i \times R_j) + (A_{i'} \times R_j)]$$

Method 3. Only the general effects from method 2 were used:

$$\hat{Y}_{(Ai \times Bi') \times Rj} = \mu + ½(g_i + g_{i'}) + g_j$$

Method 4. Parental single cross (A_i X $B_{i'}$), and restorer (R_j) data were averaged to predict the three-way cross yields:

$$\hat{Y}_{(Ai \times Bi') \times Rj} = ½[(A_i \times R_j) + R_j]$$

Method 5. A weighted average of the parental lines, the weights being their germplasm contribution to the three-way cross hybrid:

$$\hat{Y}_{(Ai \times Bi') \times Rj} = ¼[(B_i) + (B_{i'}) + 2R_j].$$

Simple correlations were calculated between predicted values obtained with each of the methods and observed values. Evaluations of the effectiveness of the prediction methods are based on these correlations.

High parent heterosis values for grain yield were calculated for single cross and three-way cross hybrids as , (SCF_1 - HP)/HP for single cross hybrids and (TWF_1 - HP)/HP for three-way hybrids. In the equations, HP is the yield of the highest yielding parent involved in the hybrid, and SCF_1 and TWF_1 are the yields of the single cross and three-way cross, respectively. Single-degree-of-freedom comparisons were used to test significance of heterotic effects.

CHAPTER IV
RESULTS AND DISCUSSION

Preliminary Evaluations at College Station in 1990

A summary of the analysis of variance together with indicated levels of significance for the F-tests for subset 1 at College Station in 1990 is shown in Table 6. Highly significant differences were indicated among the cultivars evaluated for all the characters.

The entry means are shown in Table 7; it can be seen that the hybrids uniformly outyielded the parents. The overall mean grain yield was 4548 kg/ha, with a range of 1203 kg/ha in the parental line B_2Tx637 to 6624 kg/ha for the single cross A_2Tx632*SC103-12E. Among the 10 entries that had nonsignificant differences in grain yield from the highest yielding cultivar in this trial (LSD, $P \leq 0.05$), two were single crosses, six were three-way hybrids and only one was a double cross (A_2Tx632*BTx631)*(A_2Tx637*RTx432), which yielded 5843 kg/ha (Table 7). There were significant differences among the parents and among the single crosses for all eight characters evaluated (Table 6). Three-way crosses had significant within-type differences for all the characters, except threshing percentage; whereas double cross hybrids had significantly different within-type differences in 1000-seed weight and plant height only (Table 6). Walsh and Atkins (1973) reported that significant differences for yield and several other attributes among single crosses and among three-way crosses were due largely to differences in general combining ability in the male and female parents.

The mean squares among the different types of cultivars (parents, single crosses, three-way crosses, and double crosses) indicated statistically significant differences for all the characters (Table 6). However, these differences among types were largely manifested through differences of the parents from the three hybrid types. This was more so since single-degree-of-freedom contrasts indicated highly significant differences for parents vs hybrids; otherwise, differences among the different hybrid types were not significant (Table 6) in all the characters. The different type-groups were also tested for differences using LSD ($P \leq 0.05$), and all the hybrid types were significantly different from the parental lines (Table 7). There were no significant differences indicated for any of the characters studied between the hybrid types. The means of the different hybrid types in Table 7 show a close similarity of the three hybrid types for all the characters.

Walsh and Atkins (1973) suggested that type-group means alone may not fully characterize the relative merits of the hybrid-types, however, since individual hybrids within one type-group may exceed the performance of the best hybrid in the other group, even though the group means are equivalent. Accordingly, the range of values within each group is of interest. The

Table 6. Estimated mean squares for agronomic characters in sorghum studied for subset 1 at College Station in 1990.

Source	df	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}†	d	%	g	kg hl^{-1}	cm	cm	cm
Replicates	3	110.58	5.70	82.28	0.66	5.40	428.64**	84.78**	6.37
Entries	33	865.86**	31.40**	120.84**	19.28**	61.00**	1093.18**	30.58**	55.52**
Among parents	6	210.43*	80.89**	100.78**	42.33**	37.42**	772.67**	37.16**	43.87**
Among single crosses (SC)	8	309.13**	34.63**	126.31**	4.32**	25.36**	231.80*	9.80*	73.73**
Among three-way crosses(TWC)	10	155.24*	7.02*	59.27	4.22**	21.07**	236.95**	15.61**	34.19**
Among double crosses (DC)	6	78.48	5.48	77.02	3.83**	14.06	363.28**	7.06	9.42
Types	3	7604.78**	56.86**	439.24**	94.19**	430.22**	8505.05**	169.73**	193.64**
Parents vs hybrids	1	22596.25**	158.43**	1288.64**	282.48**	1287.21**	25333.94**	490.82**	541.65**
SC vs (TWC + DC)	1	55.20	0.78	0.44	0.00	1.21	87.98	0.59	39.23*
TWC vs DC	1	162.90	11.36	28.65	0.10	2.20	93.23	0.36	0.05
Error	99	78.16	2.93	48.86	1.27	8.02	92.49	4.59	7.46
CV %		19.44	2.38	11.65	4.45	4.18	7.23	8.19	22.66

† Multiply mean squares for grain yield by 10^4.

*, ** Significantly different at 0.05 and 0.01 probability levels, respectively.

ranges for grain yield, the most important character in a crop, were 1203 to 3395 kg/ha in parental lines, 3966 to 6624 kg/ha in single crosses. Three-way hybrids had yields ranging from 4058 to 6085 kg/ha, while yields of double cross hybrids ranged between 4653 and 5843 kg/ha. Generally, the ranges of individual means among the single and three-way crosses did not differ greatly.

The within-plot standard deviations for plant height, panicle length, and panicle exsertion and the ranges are presented in the Appendix A, Table A1. The standard deviations were used as a measure of variability within a given type of cultivars. The variations in plant height were greater in the parents (11.2) than in the single cross hybrids (7.8); similarly, the variations in the three-way cross (15.4) and double cross (18.1) hybrids were greater than in the single crosses (Appendix A, Table A1). These results indicated that the single crosses were the most uniform in plant height. The variation in panicle length and exsertion did not to differ much among the types. Excessive variability for plant height in fields for commercial production would be particularly undesirable. Although the differences for standard deviations were large, it seems doubtful that they were large enough to be important agronomically. Similar observations were reported by Walsh and Atkins (1973) who reported similar statistically tested standard deviations for the different types. Rosenow (1968) suggested that considerable care should be exercised in selecting parents of sorghum so that the resulting three-way hybrid will not be excessively variable. Walsh and Atkins (1973) did not observe a strong relationship between differences in means of the parents and variability of the three-way hybrids in the range of diversity among parents encountered in their study.

Test weight is an index of grain quality for farmers and millers. In oats, high test weight has been associated with high germination, good seedling stand (Frey and Wiggans, 1956), and high milling yield (Brownlee and Gunderson, 1938). According to Hlynka and Bushuk (1959), test weight is influenced by density and packing efficiency of the grain. Grain density is a function of the biological structure and chemical composition of the grain, and packing efficiency is affected by kernel shape and uniformity (Klein et al., 1993). A three-way cross, ATx631*(A_2Tx637*RTx432) indicated the highest test weight (73 kg/hl) followed by a single cross, ATx631*B_2Tx637 (Table 7) and a double cross, (A_2Tx632*BTx631)*(A_2Tx637*RTx432) both with a test weight of 72 kg/hl. The three did not differ statistically.

Inuyama et al. (1976) and Seetharama et al. (1982) reported that reduced elongation of the peduncle in sorghum resulted in failure of pollination. This could closely be associated with the loses in the final yield. Panicle exsertion means are presented in Table 7. The cultivar that indicated the longest panicle exsertion was a single cross, A_2Tx632*RTx432 (20 cm) followed by a three-way cross (A_2Tx632*BTx631)*RTx432.

Table 7. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids in subset 1 at College Station in 1990.

Entry†	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	g	kg hl^{-1}	cm	cm	cm
Parents								
1 B_2Tx632	2088	78	52	24.4	60	105	22.1	7.9
2 BTx631	1552	77	46	23.9	63	133	27.5	4.9
3 B_2636	3395	73	58	24.5	66	109	24.3	3.8
4 B_2637	1203	76	58	22.8	64	99	19.4	12.8
5 RTx432	1530	75	53	26.2	62	111	21.8	6.7
6 SC599-11E	1968	75	51	18.4	58	98	24.0	9.6
7 SC103-12E	2384	65	60	17.7	58	89	18.3	11.4
Mean	2017 b‡	74 a	54 b	22.6 b	62 b	106 b	22.4 b	8.1 b
Single-crosses								
2*5	5582	74	62	27.2	71	149	26.0	10.9
2*6	5719	70	63	24.5	69	137	28.8	12.7
2*3	4011	75	49	25.9	68	146	28.5	12.2
2*4	5054	74	59	26.5	72	135	25.9	11.5
2*7	4387	68	63	25.2	70	128	25.7	17.3
1*5	5602	69	66	27.9	71	143	26.8	20.2
1*6	4988	69	66	25.6	71	147	27.9	18.3
1*7	6624	68	67	25.8	69	135	26.5	15.4
1*2	3966	74	57	26.6	64	128	28.6	6.2
Mean	5104 a	71 b	62 a	26.1 a	69 a	139 a	27.0 a	13.6 a
Three-way crosses								
(1*2)*5	5794	68	66	28.0	72	146	25.6	18.8
(1*2)*6	5781	71	64	25.1	68	131	27.2	14.9
(1*2)*3	4772	72	55	25.2	65	134	26.5	9.2
(1*2)*4	5001	72	65	25.4	71	124	23.7	10.3

Table 7. Continued.

Entry†	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	g	kg hl^{-1}	cm	cm	cm
Three-way-crosses								
2*(1*5)	6085	72	62	26.8	69	149	27.1	13.7
2*(1*6)	5094	72	61	24.8	68	141	28.2	11.9
2*(3*5)	5622	72	64	26.9	70	145	26.3	11.1
2*(3*6)	4058	74	62	25.7	67	143	32.4	8.4
2*(4*5)	5125	72	56	27.1	73	149	26.7	14.1
2*(4*6)	6054	72	66	25.5	70	143	27.5	13.5
2*(3*7)	5743	72	59	26.5	70	152	27.6	14.3
Means	5375 a	72 b	62 a	26.1 a	69 a	142a	27.3 a	12.6 a
Double-crosses								
(1*2)*(1*5)	4934	71	63	26.8	68	131	25.6	12.1
(1*2)*(1*6)	4578	72	58	24.8	67	133	25.5	11.2
(1*2)*(3*5)	5368	69	60	26.8	69	141	28.2	12.5
(1*2)*(3*6)	5211	72	65	25.4	67	134	27.6	11.1
(1*2)*(4*5)	5843	72	62	26.3	72	140	26.3	14.6
(1*2)*(4*6)	4653	72	65	25.3	70	137	26.9	14.1
(1*2)*(3*7)	4879	69	53	27.6	70	157	29.1	14.3
Means	5067 a	71 b	61 a	26.2 a	69 a	139a	27.1 a	12.7 a
General mean	4548	72	60	25.4	68	133	26.2	12.1
LSD(0.05)	1240	2.4	9.8	1.6	4.0	13.5	3.0	3.8

† In this table, parents in a particular cross are identified by number; e.g., 2*5 is a single cross of BTx631 and RTx432, while (1*2)*5 represents a three-way cross from the cross between B_2Tx632 by BTx631 single cross and RTx432; similarly, (1*2)*(1*5) is a double cross involving the single crosses of B_2Tx632 by BTx631 and B_2Tx632 by RTx432.

‡ Within columns, type means followed by same letter are not significantly different according to LSD ($P \leq 0.05$)

The results of the analyses of variance for subset 2 at College Station in 1990 are presented in Table 8. Differences for grain yield and all the other characters, except threshing percentage, were detected ($P \leq 0.01$), indicating variability among the cultivars evaluated. RTx430 was excluded in the analyses for grain yield, 50% anthesis, threshing percentage, test weight, and 1000-seed weight for reasons of poor germination in all the three replicates. The mean grain yield for the remaining 16 entries was 4454 kg/ha (Table 9), ranging from 6925 kg/ha in a single cross, A_2Tx632*RTx430, to 1156 kg/ha in B_2Tx637. Three entries were not significantly different from the highest yielding single cross in grain yield; these were, a single cross, A_2Tx632*RTx432 (5857 kg/ha), a double cross, (A_2Tx632*RTx430)*(A_2Tx636*RTx432) (5795 kg/ha), and another single cross, A_2Tx632*SC599-11E. The best three-way in grain yield, A_2Tx632*RTx430)*RTx432 (5666 kg/ha), was next in rank, and though it differed significantly from the best yielding single cross, it did not differ from the next three cultivars. Means for all characters are presented in Table 9. The best parental line for in yield was B_2Tx636 (4817 kg/ha).

Comparisons among cultivars within each type-group were done, and it can be seen, from Table 8, that the parents indicated high variability as a group for all characters, except for threshing percentage and panicle length. Single crosses indicated high within-type variability for 1000-seed weight, test weight, and panicle exsertion. Three-way hybrids were variable among themselves for all characters, except threshing percentage and panicle length. Among the double crosses, none of the characters indicated statistical significance for within-type differences. Comparisons among the different types were significant for all the characters (Table 8).

Single-degree-of-freedom orthogonal contrasts were performed, and parents vs hybrids mean squares indicated significant differences for all the characters. Differences also were indicated for single crosses vs three-way crosses and double crosses combined, for grain yield, 1000-seed weight, plant height, and panicle exsertion (Table 8). The single-degree-of-freedom contrast for three-way crosses vs double crosses was not significant in the range of characters under study. The least significant difference (LSD) tests among the different types confirmed the orthogonal contrasts. The single crosses outperformed all the other types in grain yield, test-weight, plant height, and panicle exsertion (Table 9). Performance of the single-crosses in this experiment was as expected from predicted genetic potential (Cockerham, 1961). Panicle exsertion recorded a very high CV (40%) implying its unpredictability as a character for improvement.

The parental line, RTx430 had very poor germination in this trial. However, it tended to combine very well in hybrid combinations resulting in high yields. RTx430 restores the A_1 cytoplasm but is a maintainer in the A_2 background. The male-sterile single cross A_2Tx632*RTx430 was used as the female parent in all the three-way crosses and the double crosses in this study. This male-sterile single cross was also the best in grain yield and had the tallest plants (141 cm).

Table 8. Estimated mean squares for agronomic characters in sorghum studied for subset 2 at College Station in 1990.

Source	df	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height‡	Panicle length‡	Panicle exsertion‡
		kg ha^{-1}†	d	%	g	kg hl^{-1}	cm	cm	cm
Replicates	3	72.71	9.46	14.88	1.06	1.81	716.47**	108.19**	16.64
Entries	15	1310.53**	38.10**	90.23	36.06**	53.81**	712.59**	45.86**	71.76**
Among parents	4	948.55**	21.93**	134.75	50.07**	39.52**	121.54	38.41**	71.68**
Among single crosses (SC)	2	163.47	6.33	22.54	11.40**	45.97**	16.08	15.16	85.63**
Among three-way crosses(TWC)	3	252.02*	15.75*	19.28	8.68**	21.71*	276.76*	15.91	49.34*
Among double crosses (DC)	3	41.58	2.83	26.43	4.43	10.52	23.00	4.06	14.64
Types	3	4885.33**	138.46**	210.76	92.84**	153.49**	3286.63**	150.50**	142.21**
Parents vs hybrids	1	13625.67**	398.26**	585.83**	264.35**	390.85**	9019.92**	419.43**	284.11**
SC vs (TWC + DC)	1	929.08**	7.00	1.39	12.48**	69.61	503.59*	21.60	120.07**
TWC vs DC	1	101.23	10.13	45.05	1.70	0.00	336.38	10.47	22.45
Error	45	71.39	4.14	78.70	1.62	5.73	93.09	8.73	13.86
CV %		18.97	2.84	13.53	5.23	3.63	8.25	11.98	40.27

† Multiply mean squares for grain yield by 10^4.
‡ For plant height, panicle length and panicle exsertion degrees of freedom for entries, among parents and error are 16, 5 and 48 respectively.
*,** Significantly different at 0.05 and 0.01 probability levels respectively.

Table 9. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids in subset 2 at College Station in 1990.

Entry†	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	g	kg hl^{-1}	cm	cm	cm
Parents								
1 B_2Tx636	4817	73	67	23.7	66	106	24.2	3.6
2 B_2Tx637	1156	76	56	21.2	65	95	18.5	10.3
3 B_2Tx632	1278	78	55	23.0	59	100	20.9	8.8
4 RTx430	-	-	-	-	-	103	24.5	0.0
5 RTx432	1500	78	61	23.4	62	109	17.0	11.1
6 SC599-11E	2697	73	67	15.2	60	95	22.9	8.1
Mean	2289 c‡	76 a	61 c	21.3b	62c	101 c	21.3b	6.5c
Single crosses								
3*5	5857	68	70	27.2	71	133	26.2	18.0
3*6	5781	71	65	24.6	72	129	29.9	13.6
3*4	6925	69	68	27.8	66	141	26.9	8.8
Mean	6188 a	69 b	68 ab	26.6a	70a	131 a	27.6a	13.5a
Three-way crosses								
(3*4)*5	5666	69	70	26.6	67	129	25.9	12.6
(3*4)*6	5032	70	69	24.3	70	124	27.5	10.3
(3*4)*1	5362	71	70	26.1	65	117	26.1	4.3
(3*4)*2	3853	74	65	23.5	66	110	22.8	8.3
Mean	4978bc	71 b	69 a	25.1a	67b	120 b	25.5a	8.9bc

Table 9. Continued.

Entry†	Grain yield	Days to 50% anthesis	Threshing percent	1000-seed weight	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	g	kg hl^{-1}	cm	cm	cm
Double crosses								
(3*4)*(1*5)	5795	70	67	26.8	65	129	25.7	9.1
(3*4)*(1*6)	5121	70	63	25.2	67	125	27.9	8.8
(3*4)*(2*5)	5315	69	67	26.0	68	128	25.9	12.4
(3*4)*(2*6)	5103	70	68	24.3	68	124	27.0	12.0
Mean	5334 b	70b	66abc	25.6a	67b	127ab	26.6a	10.6b
General mean	4454	72	66	24.3	66	117	24.7	9.2
LSD(0.05)	1203	3	13	1.8	3.4	13.7	4.2	5.3

† In this table, the parents in a particular cross are identified by number; e.g., 3*5 is a single cross of B_2Tx632 and RTx432, while (3*4)*5 represents a three-way cross from the cross between B_2Tx632 by RTx430 single cross, and RTx432; similarly, (3*4)*(1*5) is a double cross involving the single crosses of B_2Tx632 by RTx430, and B_2Tx8602 by RTx432.
‡ Type means within the same column followed by the same letter are not significantly different according to LSD (0.05).

This performance, though not conclusive, might be an indication of good combining ability in either of the parents or both. The high yield in the sterile single cross also indicates that there was an adequate supply of pollen for attaining full seed-set on the male-sterile entries. Patanothai and Atkins (1974) had to plant a mixture of early- through late-maturing fertile hybrids in rows adjacent to and at intervals within their experiments to ensure a continuing dispersal of an adequate supply of pollen to male-sterile entries.

Ranges in plant height, panicle length and panicle exsertion and their standard deviations for within-plot variation are presented in Appendix A, Table A1. The variability was higher in three-way (17.5) and double cross (17.6) hybrids as compared to single crosses (13.2). In this trial, the parental lines had the lowest within-plot variation for plant height as indicated by their low standard deviation value of 8.1. Within-plot variability for panicle length and panicle exsertion were similar for all the four type-groups.

Table 10 shows the mean squares for the characters studied in main set at College Station in 1990. Significant differences ($P \leq 0.01$) were observed among the cultivars for all the traits. A slightly high CV of 21% was recorded for grain yield and 26% for panicle exsertion in this experiment. The grain yield ranged from 538 kg/ha for RTx430 to 7321 kg/ha in a single cross, ATx631*SC103-12E (Table 11). The performance of RTx430 was due to poor germination as experienced in subset 2. The ranges of performance for some of the other characters were: 65 days 50% to flowering in SC103-12E, to 80 days in B_2Tx632 and BTx630; 64% threshing in ATx631*SC103-12E to 73%, in (A_2Tx632*BTx631)*(A_2Tx632*SC599-11E); 48 kg/hl test weight in BTx630 to 72 kg/hl in ATx631*(A_2Tx637*RTx432). The range for plant height was 128 cm in (A_2Tx632*BTx631)*(A_2Tx637*SC599-11E) to 168 cm in ATx630*SC103-12E.

The highest yielding cultivar, a single cross ATx630*SC103-12E (7321 kg/ha) was also the tallest (168 cm). Fifteen cultivars indicated nonsignificant (LSD) differences from the best yielder, out of which eight were single crosses (one of them the sterile single cross, A_2Tx632*RTx430), five three-way crosses, and two double crosses. The best three-way cross in grain yield was (A_2Tx632*BTx629)*RTx432 (6528 kg/ha) , while the highest yielding double-cross was (A_2Tx632*BTx631)*(A_2Tx636*SC103-12E) which recorded a mean grain yield of 6313 kg/ha (Table 11). The parental line BTx629, which yielded 3596 kg/ha, was the best parent for grain yield. The partitioning of the sums of squares due to cultivars into differences within each type (Table 10) indicated significant differences among parental lines and among single crosses for all the characters. Among three-way hybrids, differences for threshing percentage were nonsignificant, whereas among double crosses, variability was not significant for threshing percentage, days to 50% anthesis, and panicle length. There were highly significant ($P \leq 0.01$) differences among the different types for all the characters, as shown by the mean of squares in Table 10. These sum

Table 10. Estimated mean squares for agronomic characters in sorghum studied for main set at College Station in 1990.

Source	df	Grain yield	Days to 50% anthesis	Threshing percent	Test weight‡	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}†	d	%	kg hl^{-1}	cm	cm	cm
Replicates	3	69.39	40.33**	705.61**	3.25	1288.41**	22.19**	104.92**
Entries	141	720.72**	22.64**	122.89**	49.47**	639.72**	19.47**	54.23**
Among parents	13	367.41**	60.25**	201.66**	103.32**	751.13**	61.30**	56.48**
Among single crosses (SC)	33	336.48**	20.49**	63.64	27.96**	607.15**	18.40**	70.42**
Among three-way crosses(TWC)	53	268.69**	11.88**	74.15	21.23**	328.04**	11.56**	33.21**
Among double crosses (DC)	39	329.61**	10.06	39.25	15.81**	378.29**	6.67	19.54**
Types	3	19548.67**	237.04**	2381.70**	1007.04**	9420.09**	156.18**	688.40**
Parents vs hybrids	1	55875.33**	685.05**	7078.45**	2980.07**	21552.76**	33.71**	2000.69**
SC vs (TWC + DC)	1	2414.48**	3.09	17.43	33.03**	6419.88**	432.98**	59.42**
TWC vs DC	1	356.20	22.98*	49.23	8.03	287.63*	1.85	5.09
Error	423	99.50	5.85	52.65	4.93	56.53	4.89	8.53
CV %		21.53	3.34	11.31	3.33	5.87	8.39	26.68

† Multiply mean squares for grain yield by 10^4.

‡ For test weight, degrees of freedom for entries, among parents and error are 141, 12 and 420, respectively.

*,** Significantly different at 0.05 and 0.01 probability levels, respectively.

Table 11. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids in main set at College Station in 1990.

Entry†	Grain yield	Days to 50% anthesis	Threshing percent	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	kg hl^{-1}	cm	cm	cm
Parents							
1 BTx630	645	80	54	48	129	28.8	4.6
2 BTx631	1890	77	45	59	130	32.3	1.9
3 B8106	1783	79	47	55	119	33.5	1.9
4 BTx629	3596	73	65	65	125	24.1	10.4
5 B_2Tx632	766	80	61	53	98	20.4	6.4
6 B_2Tx636	3102	75	57	63	110	24.7	6.6
7 B_2Tx637	1711	75	60	67	99	20.9	13.2
8 RTx432	1230	77	53	62	115	23.8	7.6
9 SC599-11E	1889	74	57	61	91	24.3	7.8
10 SC103-12E	2540	65	59	60	90	23.4	5.0
11 RTx435	297	79	42	-	97	23.7	3.1
12 RTAM428	1460	78	54	59	109	23.7	0.4
13 RTx2737	1427	74	51	59	106	28.5	4.3
14 RTx430	538	77	42	62	118	27.9	-0.6
Means	1634 c‡	76 a	55 b	60 b	110 c	25.8b	5.3b
Single crosses							
1*8	5283	72	67	69	157	25.2	15.2
1*9	4440	73	66	65	151	29.9	14.2
1*10	7321	69	68	71	168	28.2	17.6
1*6	4199	74	61	63	144	26.3	11.5
1*7	4722	74	66	69	137	25.4	14.3
2*8	6508	71	71	71	144	27.4	7.6
2*9	4965	75	64	68	144	30.8	11.0
2*10	6880	71	62	69	159	31.4	13.1
2*6	4691	73	56	65	144	29.4	10.3
2*7	5159	75	65	71	134	28.8	11.4
2*8	5290	72	72	71	152	25.7	15.4
4*9	5899	69	70	67	138	28.9	15.4
4*6	4530	73	60	67	124	26.7	7.2
4*7	5498	74	71	71	131	25.1	14.9
3*8	4683	76	63	68	145	31.3	8.6
3*6	4463	74	60	64	121	31.7	4.1
3*7	3751	75	62	67	125	28.5	11.4
5*8	6198	69	72	70	137	25.3	17.4
5*9	6111	68	67	71	131	28.1	18.3
5*10	6428	68	67	69	141	28.8	15.3
6*8	4823	72	59	70	132	26.4	13.3
6*9	5270	70	68	67	129	29.8	11.0
6*10	6453	70	68	68	150	30.7	13.9
7*8	4182	75	67	72	115	23.4	17.1
7*9	4563	71	65	71	116	25.5	19.1
7*10	6218	72	69	69	129	24.9	20.2

Table 11. Continued.

Entry	Grain yield	Days to 50% anthesis	Threshing percent	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	kg hl^{-1}	cm	cm	cm
Single crosses							
5*4	5933	74	63	69	129	30.3	8.4
5*1	4274	74	67	66	139	27.9	5.0
5*2	4020	76	60	66	128	28.7	7.0
5*3	5421	73	64	68	126	29.0	9.2
5*14	6672	72	69	64	134	29.5	8.0
5*11	5470	74	67	67	131	27.9	9.1
5*12	4804	73	66	66	129	27.4	6.9
5*13	5828	71	68	68	124	27.4	11.1
Means	5322 a	72 b	66 a	68 a	136 a	28.0a	12.1a
Three-way crosses							
1*(5*8)	4423	73	65	66	144	26.3	13.0
1*(5*9)	3581	74	58	64	136	25.2	12.0
1*(6*8)	4054	72	64	65	142	25.7	12.0
1*(6*9)	4274	72	61	68	134	26.5	10.5
1*(6*10)	5227	72	62	66	150	25.9	11.6
1*(7*8)	5144	74	70	70	132	23.3	12.3
1*(7*9)	4514	72	65	70	137	24.7	15.2
2*(5*8)	5319	73	64	68	134	25.8	9.3
2*(5*9)	6266	71	70	68	131	29.8	8.5
2*(6*8)	4823	75	61	69	138	27.5	9.9
2*(6*9)	5518	73	58	63	140	29.8	7.2
2*(6*10)	5951	71	66	71	146	28.0	11.9
2*(7*8)	5542	74	69	72	133	25.9	10.2
2*(7*9)	4797	73	66	71	133	26.3	12.1
4*(6*8)	5554	70	68	70	126	24.3	12.5
4*(6*9)	5441	72	65	67	128	26.4	11.8
4*(7*8)	5821	72	69	71	132	24.1	13.3
4*(7*9)	5275	71	69	69	126	24.2	14.3
3*(6*8)	4279	75	60	64	129	27.4	12.8
3*(6*9)	4600	73	61	64	128	29.6	9.0
3*(7*8)	3985	76	56	67	131	28.0	14.4
3*(7*9)	5041	75	67	68	129	27.5	11.5
5*(5*8)	3060	74	58	66	118	25.4	12.9
5*(5*9)	4020	72	69	66	108	24.5	8.5
5*(6*10)	4703	74	67	70	128	25.8	8.4
(5*1)*8	6219	70	70	68	141	24.4	15.6
(5*1)*9	5415	70	69	68	136	26.5	16.0
(5*1)*6	5364	72	62	66	130	25.2	7.9
(5*1)*7	5533	72	72	70	117	22.1	11.4
(5*2)*8	5903	71	65	70	142	24.9	15.0
(5*2)*9	5488	72	71	69	132	29.6	11.3
(5*2)*6	5449	73	63	68	123	27.5	8.4
(5*2)*7	3783	74	65	70	118	24.8	8.1

Table 11. Continued.

Entry	Grain yield	Days to 50% anthesis	Threshing percent	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha-1	d	%	kg hl-1	cm	cm	cm
Three-way crosses							
(5*4)*8	6528	70	72	68	136	23.9	16.0
(5*4)*9	5331	71	63	69	129	26.9	13.3
(5*3)*8	6225	70	68	69	135	26.5	15.9
(5*3)*9	5889	72	70	68	128	27.8	13.4
(5*3)*6	3362	75	59	64	120	24.8	7.8
(5*3)*7	5128	73	68	68	114	26.6	7.8
(5*14)*8	5833	69	68	68	130	25.2	12.2
(5*14)*9	5851	68	67	68	122	27.4	12.1
(5*14)*6	4047	74	57	62	115	26.3	5.4
(5*14)*7	4483	73	56	68	118	23.9	11.7
(5*11)*8	4590	73	68	67	128	26.1	13.2
(5*11)*9	4681	70	65	67	124	27.5	11.9
(5*11)*6	3726	73	63	65	115	24.5	4.5
(5*11)*7	3810	73	62	66	117	23.9	10.6
(5*12)*8	4525	74	70	66	131	25.3	12.4
(5*12)*9	4388	72	65	69	117	24.8	12.3
(5*12)*6	4789	72	63	66	128	26.6	5.8
(5*12)*7	3773	75	62	67	120	24.5	12.9
(5*13)*8	4704	71	67	68	130	25.3	16.5
(5*13)*9	5055	71	68	66	123	24.6	14.9
(5*13)*6	4280	69	61	62	131	25.0	11.4
Means	4914 b	72 b	65 a	67 a	129 b	26.0b	11.5a
Double crosses							
(2*1)*(5*8)	5531	72	67	67	141	23.8	12.5
(2*1)*(5*9)	5450	72	68	66	145	26.6	17.4
(2*1)*(6*9)	6142	69	66	69	161	25.9	16.0
(5*1)*(5*8)	5000	72	64	66	135	25.7	12.5
(5*1)*(5*9)	4863	71	68	66	129	23.6	11.1
(5*1)*(6*8)	5565	72	69	67	133	24.2	10.5
(5*1)*(6*9)	5213	71	65	67	136	26.7	11.4
(5*1)*(6*10)	4586	73	59	70	137	27.9	10.8
(5*1)*(7*8)	5732	71	69	71	131	24.0	12.7
(5*1)*(7*9)	5169	71	68	69	129	24.5	12.6
(5*2)*(5*8)	5031	72	73	68	126	24.3	10.5
(5*2)*(5*9)	5117	70	68	66	120	25.9	8.8
(5*2)*(6*8)	5391	73	61	68	136	26.3	11.5
(5*2)*(6*9)	5631	70	67	66	125	25.2	10.3
(5*2)*(6*10)	6313	70	64	70	145	26.3	11.1
(5*2)*(7*8)	3631	75	66	69	122	26.4	9.6
(5*2)*(7*9)	4885	71	67	69	128	27.1	13.7
(5*4)*(6*8)	5398	72	64	68	132	24.6	12.5
(5*4)*(6*9)	5588	71	65	68	128	27.4	11.0

Table 11. Continued.

Entry	Grain yield	Days to 50% anthesis	Threshing percent	Test weight	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	d	%	kg hl^{-1}	cm	cm	cm
Double crosses							
(5*9)*(7*8)	5512	70	69	69	126	24.9	14.1
(5*9)*(6*9)		5054	71	69	70	124	25.013.5
(5*3)*(6*8)	4335	73	65	66	124	26.4	9.6
(5*3)*(6*9)	4730	72	65	65	128	29.9	9.1
(5*3)*(7*8)	4777	74	67	69	123	26.5	11.9
(5*3)*(7*9)	4531	73	66	67	121	26.9	11.8
(5*14)*(6*8)	4996	72	68	65	131	27.3	10.1
(5*14)*(6*9)	5278	71	69	66	125	26.9	10.1
(5*14)*(7*8)	4150	73	61	68	121	25.7	10.1
(5*14)*(7*9)	4267	72	69	67	116	27.0	9.9
(5*11)*(6*8)	3237	73	65	64	123	26.6	8.0
(5*11)*(6*9)	2846	75	59	63	118	25.9	8.2
(5*11)*(7*8)	4245	72	64	66	121	25.4	11.3
(5*11)*(7*9)	2297	75	59	63	125	24.9	11.5
(5*12)*(6*8)	5051	72	65	69	125	25.8	7.8
(5*12)*(6*9)	3907	73	61	67	120	26.3	8.2
(5*12)*(7*8)	3146	74	61	68	116	23.6	10.0
(5*12)*(7*9)	4248	72	67	69	112	24.8	8.7
(5*13)*(6*8)	3886	69	67	65	116	24.8	13.0
(5*13)*(7*8)	4761	69	64	69	126	25.8	16.3
(5*13)*(7*9)	3200	70	65	63	110	26.1	9.8
Means	4717 b	72 b	66 a	67 a	127 b	25.8b	11.2a
General means	4633	73	64	67	128	26.4	11.0
LSD(0.05)	1386	3.4	10	3.1	10.5	4.1	3.1

† Parents in a particular cross are identified by number; e.g., 1*8 is a single cross of ATx630 by RTx432, while 1*(5*8) represents a three-way cross of ATx630, and the cross between A_2Tx632 and RTx432; similarly, (2*1)*(5*8) is a double cross involving the single crosses of ATx631 by BTx630, and A_2Tx632 by RTx432.

‡ Type means within the same column followed by the same letter are not significantly different according to LSD (0.05).

of squares due to the differences among types were partitioned, by single-degree-of-freedom orthogonal contrasts, into various useful comparisons. The hybrids as a group uniformly outperformed the parental lines in all the studied characters. The hybrids expressed higher grain yields, threshing percentage, and test weight, were earlier in flowering, had taller plants, longer panicles, and exsertion. These observations are in agreement with Quinby (1963), who found heterosis to be expressed in the hybrids through earlier anthesis, increased height, larger panicles, higher threshing percentage, and greater production of grain among other characters.

The orthogonal contrast for single crosses vs three-way crosses and double crosses combined (Table 10) indicated nonsignificant differences for days to 50% anthesis and threshing percentage. The comparison for three-way hybrids vs double crosses indicated some significant difference for days to 50% anthesis ($P = 0.0482$). To confirm the individual type differences in performance among each type-group, the LSD ($P = 0.05$) test was performed. This test indicated that single crosses had outperformed the three-way crosses and double crosses in grain yield, plant height, and panicle length (Table 11). Three-way hybrids and double crosses did not differ significantly for any of the attributes in the study.

The ranges for individual plot means within the different type-groups and the within-plot standard deviations are presented in Appendix A, Table A1. The three-way crosses (20.74) and double crosses (22.17) indicated the greater within-plot variability, as evidenced by their standard deviations, than the single crosses (15.28). The parental lines in this trial were the least variable for plant height within-plot . These results are similar to those observed in subset 1 and subset 2, and indicate that within-plot variability is expected to be higher in the multi-crosses than in single crosses. The level of variability in the three-way crosses, however, could be controlled by selection of parents to be used in the production of the hybrid, if production is found feasible (Rosenow, 1968).

Texas Trials in 1991 and 1992

Individual Location Analysis for Trials in Texas

Estimated mean squares and means of performance for grain yield and other characters for the individual location-year combination, at each of the four sites in Texas, 1991 and 1992 are presented in the following tables. The analysis of variance table for College Station in each of the years is presented in Table 12. At College Station, data for grain yield, days to 50% anthesis, and plant height were recorded for each of the two years; 1000-seed weight, panicle length, and panicle exsertion were measured only in 1991 (Tables 12 and 13). In both years at College

Table 12. Estimated mean squares for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at College Station in 1991 and 1992.

		Grain yield kg ha^{-1}†		1000-seed weight g	Days to 50% anthesis d		Plant height cm		Panicle length cm	Panicle exsertion cm
Source	df	1991	1992	1991	1991	1992	1991	1992	1991	1991
Replicates	2	5012.32**	115.46	16.06**	125.20**	1.92	350.09**	340.69*	4.94	61.20**
Entries	51	473.58**	455.93**	19.58**	50.56**	24.18**	746.94**	931.31**	13.02**	80.47**
Parents (P)	7	300.11*	247.14	18.98**	122.23**	70.23**	1153.72**	778.27**	43.36**	136.09**
SC	18	338.65**	349.93**	16.68**	28.39**	14.69**	105.40**	745.12**	8.61	62.60**
TWC	14	307.18*	426.55**	15.26**	12.18	13.02**	219.60**	517.80**	7.10	14.76
DC	9	166.59	163.30	4.18**	11.50	7.50*	288.71**	526.68**	1.95	8.48
Types	3	3385.45**	2594.07**	104.81**	312.66**	75.70**	5803.52**	5549.14**	29.60**	580.46**
P vs hybrids	1	7833.22**	7567.11**	301.44**	893.36**	217.01**	16297.76**	16511.47**	61.41**	1692.13**
SC vs (TWC+DC)	1	2322.47**	58.46	1.55	36.61*	5.80	1015.33**	84.00	27.31*	0.19
TWC vs DC	1	0.66	156.63	11.45**	8.00	4.30	97.46	51.95	0.08	49.06*
Error	102	140.24	160.88	1.60	7.62	3.82	40.07	84.02	4.08	9.04
CV %		27.96	34.20	4.07	3.75	2.57	4.81	7.03	7.44	16.69

† Mean squares equal 10^4 times the column values.

*, ** Significant at .05 and .01 probability levels, respectively.

Station, cultivar effects were highly significant for all the characters studied as shown in Table 12. The sums of squares for entries were partitioned into the different type-groups. Differences among the parental lines were found to be highly significant for all the traits, except for grain yield in 1992. Variation among the single crosses were highly significant for all the characters, except in panicle length, which was measured in 1991 only. Among three-way crosses, significant differences were indicated for grain yield and plant height in both years, but only in one year, 1992, for days to 50% anthesis. 1000-seed weight, measured in 1991 but not 1992, was also variable among the three-way hybrids. The double crosses indicated nonsignificant differences for grain yield in both years, days to 50% anthesis in 1991, and panicle length.

The different type-groups indicated highly significant differences in all the characters measured when compared, as shown by the significant mean squares for types in Table 12. The sums of squares for types were partitioned into the appropriate three single-degree-of-freedom contrasts. Highly significant differences were indicated for parents vs hybrids for all the characters studied in both years (Table 12). The contrast single crosses vs three-way crosses and double crosses combined was significant for all the characters in 1991, except panicle exsertion and 1000-seed weight, but not significant for any of the characters measured in 1992. Three-way crosses vs double cross hybrids contrast indicated significant differences for only 1000-seed weight and panicle exsertion in 1991; the contrast was nonsignificant for all the traits measured in 1992.

The mean performances for each of the two years, at College Station, are as shown in Table 13. The overall location-year mean grain yield for 1991 was 4236 kg/ha. The cultivars had mean grain yields ranging from 743 kg/ha in a parental line, RTx430, to 6999 kg/ha in a three-way cross, (ATx631*BTx630)*SC599-11E. The parental line, RTx430 recorded poor stands in all the replicates as, similarly, reported in the preliminary evaluation trials earlier, and this should have contributed to the low yields for the line. Eleven cultivars indicated nonsignificant differences (LSD, P = 0.05) for grain yield from the highest yielding cultivar; of which nine were single crosses, and two were three-way crosses.

The ranges in grain yield among the different type-groups were 743 to 3833 kg/ha among parental lines, 3198 to 6762 kg/ha among single crosses, 3028 to 6999 kg/ha among three-way crosses, and 3265 to 5428 kg/ha among double crosses. Parental lines recorded a within-type-group mean grain yield of 2574 kg/ha, single crosses had a mean grain yield of 5019 kg/ha, three-way crosses 4180 kg/ha, whereas double crosses yielded 4161 kg/ha. Mean comparisons of the different type-groups for grain yield in 1991 at College Station, according to Fisher's LSD test (P = 0.05), indicated significant differences for the hybrid-types from parental lines. Single cross mean yield was significantly different from the three-way crosses and the double crosses. However, the three-way hybrids and double crosses were not significantly different for mean grain yield.

Table 13. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at College Station in 1991 and 1992.

	Grain yield kg ha^{-1}		1000-seed weight g	Days to 50% anthesis d		Plant height cm		Panicle length cm	Panicle exsertion cm
Entry†	1991	1992	1991	1991	1992	1991	1992	1991	1991
Parents									
1 BTx630	2102	1672	24.8	89	81	138	136	28.8	10.4
2 BTx631	2656	3029	29.2	82	80	134	126	29.1	7.4
3 B2.Tx632	1870	2534	29.1	82	83	99	102	21.2	20.5
4 B_2Tx636	3832	1805	27.3	80	80	106	96	25.3	6.8
5 RTx430	743	271	29.7	83	86	102	94	30.7	-2.6
6 RTx432	2632	3140	30.2	76	76	110	108	22.7	13.9
7 SC103-12E	3533	1985	29.1	68	70	81	90	20.8	12.7
8 SC599-11E	3223	2201	23.3	74	76	92	99	26.9	13.3
Means	2574 c‡	2080 b	27.9b	79 a	79 a	108 c	106 b	25.7b	10.3b
Single crosses									
1*2	3198	2143	28.2	81	79	149	148	28.1	9.7
1*3	3515	4779	31.8	75	77	142	141	26.9	18.5
1*4	4069	3721	28.8	75	76	138	126	27.7	16.0
1*6	4258	2254	30.4	74	79	156	150	27.1	20.7
1*7	3972	2775	33.1	67	73	158	167	27.5	25.8
1*8	6762	3544	28.3	74	75	146	127	26.4	24.4
2*3	3838	5267	34.6	73	79	136	124	27.0	20.3
2*4	5196	4339	30.5	75	75	136	119	30.4	15.0
2*5	5872	3497	33.5	73	78	143	134	30.8	12.1
2*6	5056	5555	30.6	74	75	152	146	27.6	18.8
2*7	6256	3561	33.4	73	74	153	158	30.0	24.3
2*8	6012	5823	30.2	75	75	137	144	31.5	16.7
3*5	5757	5275	35.4	73	79	126	125	28.6	17.5
3*6	4898	5015	34.8	73	76	134	126	25.1	28.1
3*7	4228	4785	35.4	68	73	134	148	26.4	21.0
3*8	4916	2988	32.8	70	78	117	113	27.4	22.5
4*6	5501	4018	31.3	71	75	130	115	26.0	20.6
4*7	5324	4140	32.1	72	72	136	126	27.8	20.6
4*8	6731	4167	29.2	76	74	121	112	28.8	17.5
Means	5019 a	4087 a	31.8a	73 b	76 b	139 a	134 a	28.0a	19.5a
Three-way crosses									
(3*1)*6	4453	6194	31.7	73	75	142	142	26.4	24.7
(3*1)*7	4587	4871	33.4	71	71	137	155	25.0	22.7
(3*1)*8	4289	4558	28.4	74	76	127	129	26.7	22.8
1*(4*6)	3058	4250	28.5	75	74	137	130	24.9	17.4

Table 13. Continued.

Entry	Grain yield kg ha^{-1}		1000-seed weight g	Days to 50% anthesis d		Plant height cm		Panicle length cm	Panicle exsertion cm
	1991	1992	1991	1991	1992	1991	1992	1991	1991
Three-way crosses									
1*(4*7)	3521	2888	31.2	70	74	138	150	25.6	19.5
1*(4*8)	3716	3561	27.9	72	74	128	125	27.0	18.3
2*(3*6)	3350	5793	32.1	74	75	138	141	26.6	21.0
2*(3*8)	4508	3893	31.7	75	76	131	128	29.2	17.3
2*(3*7)	3271	3771	33.0	71	75	148	151	27.3	21.8
2*(4*6)	4380	4433	31.0	71	78	137	137	28.2	17.6
3*(4*7)	3028	2730	33.2	70	80	121	142	25.6	19.1
(2*1)*6	5281	5460	29.9	75	75	147	147	26.9	18.5
(2*1)*8	6999	2506	28.8	75	77	138	125	29.0	20.9
(3*5)*7	4033	3921	36.0	71	73	124	138	27.5	19.9
(3*5)*8	4222	2223	32.3	70	76	122	104	30.1	19.4
Means	4180 b	4070 a	31.3a	73 b	75 b	132 ab	136 a	27.1a	20.1a
Double crosses									
(2*1)*(3*6)	3387	4278	33.1	73	77	136	131	26.4	21.4
(2*1)*(3*7)	4508	2445	33.1	72	75	138	154	27.1	19.2
(2*1)*(3*8)	4416	4239	30.1	75	78	132	124	27.2	19.4
(2*1)*(4*7)	5428	4369	33.0	73	74	155	160	26.7	20.2
(3*1)*(4*6)	5050	4051	31.6	72	75	128	134	25.4	17.9
(3*1)*(4*8)	3277	2694	30.1	69	76	124	122	27.6	16.6
(3*1)*(4*7)	3265	3464	32.0	73	75	126	140	27.9	15.8
(3*2)*(4*6)	3813	4073	33.3	69	75	126	127	26.3	18.2
(3*2)*(4*8)	4002	3475	32.2	69	79	122	122	27.9	17.7
(3*2)*(4*7)	4459	4663	32.2	73	75	134	132	27.5	17.6
Means	4161 b	3775 a	32.1a	72 b	76 b	132 b	135 a	27.0 ab	18.4a
General means	4236	3713	31.1	74	76	132	131	27.2	18.0
LSD (0.05)	1918	2054	2.1	5	3	10	15	3.3	4.9

† Parents in a particular cross are identified by number; e.g. 1*2 is a single cross of ATx630 by BTx631, while (3*1)*6 represents a three-way cross of the single cross A_2Tx632 by BTx630, and the parent RTx432; similarly, (2*1)*(3*6) is a double cross involving the single crosses of ATx631 by BTx630, and A_2Tx632 by RTx432.

‡ Type means in the same column followed by similar letter are not significantly different according to LSD (0.05).

In 1992, at College Station, a grain yield mean of 3713 kg/ha was recorded (Table 13), with the cultivar range of 271 kg/ha in RTx430 to 6194 kg/ha in a three-way hybrid, (A_2Tx632*BTx630)*RTx432. Nineteen cultivars were not significantly different from the best yielding cultivar (LSD, P = 0.05), eight of which were single crosses, seven three-way crosses, and four double crosses. The ranges for each type at College Station in 1992 were 271 to 3140 kg/ha among parental lines, 2143 to 5823 kg/ha among single crosses, and 2223 to 6194 kg/ha among double crosses. The mean grain yields for each of the hybrid-groups did not differ significantly from each other (LSD, P=0.05) as shown in Table 13. Each of the hybrid-groups yielded significantly more than the parental lines.

1000-seed weight at College Station was measured in 1991 but not in 1992. The overall cultivars mean was 31.1 g, ranging from 23.3 g, in SC599-11E, to 36.0 g in a three-way cross, (A_2Tx632*RTx430)*SC103-12E (Table 13). Four single cross hybrids did not differ significantly (LSD, P = 0.05) from the cultivar with the highest 1000-seed weight. The ranges among cultivars within a type-group were 23.3 to 30.2 g for parental lines, 28.2 to 35.4 g for single crosses, 27.9 to 36.0 g among three-way crosses, and 30.1 to 33.3 g among double cross hybrids. The type means for 1000-seed weight were 27.9 g in parental lines, 31.8 g for single crosses, 31.3 g for three-way crosses, and 32.1 g for double crosses. The different hybrid-types differed significantly (LSD, P = 0.05) from the parental single crosses, but did not differ significantly among themselves.

The character days to 50% anthesis, in 1991 at College Station, indicated an overall mean of 74 d, while in 1992 the mean was 76 d (Table 13). The range in 1991 was 67 d in a single cross ATx630*SC103-12E, to 89 d in a parental line ATx630. The earliest single cross involved an early parent, SC103-12E and a late parent, ATx630 (89 d). The range for days to 50% flowering in 1992 was 70 d in SC103-12E to 86 d in RTx430. The mean days to 50% flowering, for each of the type-groups, ranged from 68 to 89 d, and 70 to 86 d in parental lines for 1991 and 1992, respectively; 67 to 89 d in 1991 and 72 to 79 d in 1992 among single crosses, 70 to 75 d in 1991 and 71 to 80 d in 1992 among three-way crosses, and 69 to 75 d in 1991 and 74 to 79 d in 1992 for the double crosses. The mean days to 50% anthesis in the parental lines were 79 d in 1991 and 1992, for single crosses were 73 d in 1991 and 76 d in 1992, among three-way crosses 73 d and 75 d in 1991 and 1992, respectively; while double crosses took 72 d in 1991 and 76 d in 1992. The LSD test indicated the three hybrid-types similar in days to 50% flowering, and significantly earlier than the parental lines in both years at College Station (Table 13).

The parental line SC103-12E had the shortest plants in both years, 81 cm in 1991 and 90 cm in 1992, while the single cross, ATx630*SC103-12E was the tallest, 158 cm and 167 cm in 1991 and 1992, respectively. Four single crosses and, one three-way cross and double cross each, were not significantly different from the tallest cultivar in 1991, whereas one single cross and three-way cross each indicated similar heights with the tallest cultivar. The mean plant heights for College Station in 1991 and 1992 were 132 cm and 130 cm, respectively. Parental lines had a mean plant height of 108 cm in 1991 and 106 cm in 1992, single crosses 139 cm and 134 cm, respectively, three-way crosses 134 cm and 136 cm, and double crosses 132 cm and 135 cm, for each of the two years. In 1991, single cross mean plant height was similar to that of three-way crosses but significantly more than for double crosses and parental lines. Three-way crosses did not differ from the double crosses (Table 13). Plant height for the three hybrid-types were similar in 1992, and these were significantly different from the parental lines.

Panicle length at College Station in 1991 ranged from 20.8 cm in SC103-12E, to 31.5 cm in a single cross ATx631*SC599-11E. The overall mean panicle length was 27.2 cm with the parental lines having a mean of 25.7 cm, single crosses 28.0 cm, three-way crosses 27.1 cm, and double crosses 27.0 cm. The mean panicle length among the hybrid-types were not significantly different, however, the double crosses also indicated non-significant differences with the parental lines. Panicle exsertion ranged from -2.6 cm in RTx430 to 28.1 cm in A_2Tx632*RTx432. The overall panicle exsertion was 27.2 cm, with type means of 10.3 cm among parental lines, 19.5 cm among single crosses, 20.1 cm among three-way hybrids and 18.4 cm among double crosses. Significant differences were indicated between each of the hybrid-types and the parental lines, but the hybrid-types were not significantly different (LSD; $P = 0.05$) from each other.

The mean squares for each of the two years, 1991 and 1992, at Halfway, Texas are shown in Table 14 for all the characters in this study. Similar data were recorded in the two years as for College Station, with grain yield, days to 50% anthesis and plant height being measured in both years, while 1000-seed weight, panicle length and panicle exsertion were measured only in 1991. Highly significant cultivar differences were indicated for all the characters in both years except plant height in 1992 (Table 14). Partitioning of the sums of squares for entries into the variations due to differences among each type-group, indicated significant differences among parents and among single crosses for all characters except plant height in 1992. Variability among three-way crosses was significant for all characters except days to 50% anthesis and plant height in 1992. Among double crosses, variability was indicated only for 1000-seed weight and plant height in 1991.

The variability among the different type-groups was highly significant for most of the characters except 1000-seed weight and, in 1992, plant height (Table 14). Partitioning of the sums of squares due to differences among types into single-degree-of-freedom orthogonal contrasts indicated parents vs hybrids to be significantly different ($P \le 0.01$) for all the characters except plant height in 1992, which indicated significance at the 0.05 probability level. The contrast

Table 14. Estimated mean squares for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Halfway in 1991 and 1992.

Source	df	Grain yield kg ha^{-1} 1991	Grain yield kg ha^{-1} 1992	1000-seed weight g 1991	Days to 50% anthesis d 1991	Days to 50% anthesis d 1992	Plant height cm 1991	Plant height cm 1992	Panicle length cm 1991	Panicle exsertion cm 1991
Replicates	*2*	*161.18*†	*1678.70***†	*1.67*	0.58	28.31*	58.31	144.96	7.65	5.82
Entries	51	553.43**	855.49**	26.01**	12.75**	36.26**	856.39**	212.88	17.93**	50.99**
Parents (P)	7	269.99*	940.66**	32.53**	58.17**	94.00**	762.53**	233.89	36.65**	91.46**
SC	18	226.16**	503.78**	33.58**	5.33**	47.53**	574.45**	153.95	16.71**	54.09**
TWC	14	307.18**	478.27**	15.26**	4.12**	6.33	338.71**	216.82	8.30**	19.16*
DC	9	138.20	66.49	13.07**	0.59	3.12	312.46**	230.53	4.27	8.41
Types	3	6405.37**	6894.30**	5.54	28.05**	73.02**	6814.70**	446.01	67.38**	214.24**
P vs hybrids	1	18568.30**	19644.63**	14.82**	80.01**	194.01**	19953.07**	1194.23*	149.32**	602.07**
SC vs (TWC+DC)	1	567.95*	917.93*	0.65	4.00	18.81	100.88	141.03	45.90**	0.21
TWC vs DC	1	79.86	120.34	1.49	0.14	6.24	390.14**	2.75	6.92	40.44*
Error	102	100.93	195.33	2.16	1.05	6.79	37.41	208.27	2.94	10.05
CV %		13.49	20.63	4.61	1.43	3.66	4.23	10.98	5.75	20.27

† Mean squares equal 10^4 times the column values.
*, ** Significant at 0.05 and 0.01 probability levels, respectively.

single crosses vs three-way crosses and double crosses combined indicated significant ($P \leq 0.05$) for grain yield in both years, and highly significant ($P \leq 0.01$) differences for panicle length. Three-way crosses vs double crosses was significant for plant height in 1991 and panicle exsertion. The least significant differences (LSD) test was used to separate the means especially for those types that could not be compared usefully by the orthogonal contrasts procedure. The hybrid types were shown to uniformly outperform the parental lines for all the characters (Table 15). The differences between the single crosses and the three-way hybrids were not significant for the characters studied, while the single crosses had significantly higher grain yields than the double crosses in 1991.

The mean performances at Halfway during 1991 and 1992 are presented in Table 15. Higher yields were recorded at this location in both years compared to College Station. The overall cultivars mean grain yield in 1991 was 7447 kg/ha, while in 1992 the mean was 6776 kg/ha. The range in grain yield for 1991 was 10,096 kg/ha in a single cross, A_2Tx632*SC103-12E to 3029 kg/ha in RTx430. The best three-way cross was A_2Tx632*(A_2Tx636*SC103-12E) with a grain yield of 9112 kg/ha. Among double crosses, (A_2Tx632*RTx430)*(A_2Tx636*RTx432) was the highest yielding at 8769 kg/ha. These high yielding multi-crosses did not differ significantly (LSD test) from the highest yielding single cross. In 1992 grain yield, at Halfway, ranged from 540 kg/ha in RTx430 to 9636 kg/ha in a single cross, ATx631*SC103-12E. The best three-way cross was ATx630*(A_2Tx636*SC103-12E) with 8851 kg/ha grain yield. The highest grain yielder among double crosses was (A_2Tx632*BTx630)*(A_2Tx636*SC599-11E.

1000-seed weight had an overall cultivars location mean of 31.9 g at Halfway in 1991. The cultivars ranged in seed weight from 26.1 g in B_2Tx636 to 39.5 g in a single cross, ATx630*SC103-12E. A three-way cross (A_2Tx632*RTx430)*SC103-12E was second in rank for 1000-seed weight, and indicated nonsignificant difference (LSD) with the single cross (Table 15). Days to 50% anthesis in 1991 ranged from 69 d in a three-way cross, ATx630*(A_2Tx636*RTx432), to 84 d in a parental line A_2Tx636. In 1992, days to 50% anthesis, at Halfway, ranged from 66 d in a single cross, ATx631*SC103-12E to 86 d in A_2Tx636. The mean days to 50% anthesis at this location were 72 d and 71 d in 1991 and 1992, respectively. The hybrids were earlier than the parental lines in both years according to the LSD tests among the type-groups.

Plant height at Halfway indicated significant differences among cultivars during 1991 but not in 1992. The overall cultivars locational mean for 1991 was 145 cm with a range of 96 cm in SC103-12E to 182 cm in the single cross ATx630*SC103-12E. A three-way cross, (A_2Tx632*BTx630)*SC103-12E (174 cm), was the second ranking in plant height, and did not differ significantly from the tallest cultivar. The hybrid-types indicated significant (LSD) superiority over the parental lines in plant height (Table 15). Panicle length ranged from 22.5 cm in SC103-12E

Table 15. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Halfway in 1991 and 1992.

	Grain yield kg ha^{-1}		1000-seed weight g	Days to 50% anthesis d		Plant height cm		Panicle length cm	Panicle exsertion cm
Entry†	1991	1992	1991	1991	1992	1991	1992	1991	1991
Parents									
1 BTx630	5350	4834	32.2	74	74	147	125	29.5	13.7
2 BTx631	5924	4016	31.3	72	75	134	119	32.0	12.0
3 B_2Tx632	4866	3063	31.0	84	85	120	121	24.3	15.7
4 B_2Tx636	5973	6153	26.1	70	69	117	118	27.0	12.7
5 RTx430	3029	540	36.9	73	73	110	138	32.0	0.0
6 RTx432	5004	4899	33.0	71	72	113	134	25.2	9.1
7 SC103-12E	4348	5761	31.0	71	67	96	131	22.5	7.5
8 SC599-11E	4611	3885	27.6	72	74	108	113	27.7	17.5
Means	4888 c‡	4144 b	31.2a	73 a	74 a	118 b	125 b	27.5c	11.0b
Single crosses									
1*2	6656	4562	35.4	72	76	149	121	31.4	11.2
1*3	9066	7432	32.1	74	75	166	122	28.5	22.6
1*4	7754	7423	28.3	71	66	147	128	29.1	16.3
1*6	7211	7469	33.1	72	70	172	135	28.1	20.0
1*7	7576	9498	39.5	70	67	182	136	32.2	12.9
1*8	8195	9351	31.3	71	70	154	136	32.7	17.9
2*3	7806	5920	31.8	72	75	143	126	32.5	18.1
2*4	7907	8257	27.7	70	68	137	132	32.9	11.6
2*5	7766	6849	33.4	71	72	144	131	36.9	6.9
2*6	7469	8677	32.7	72	70	158	131	29.7	17.1
2*7	8680	9636	36.4	71	66	164	133	32.6	16.7
2*8	7855	7916	29.5	71	69	145	144	32.5	19.8
3*5	9535	5684	31.9	73	79	142	129	32.2	14.1
3*6	7564	7352	32.7	73	76	145	125	29.1	21.2
3*7	10096	7411	35.7	74	75	159	122	27.5	10.2
3*8	8885	7282	27.6	73	73	138	125	31.1	21.7
4*6	7760	7269	27.6	71	70	134	141	27.5	17.1
4*7	9216	7089	31.9	70	68	155	146	30.3	19.2
4*8	7846	8508	27.7	70	67	128	134	30.8	17.6
Means	8150 a	7557 a	31.9a	72 b	71 b	151 a	131 ab	30.9a	16.4a
Three-way crosses									
(3*1)*6	8364	6859	32.8	71	69	150	132	27.4	19.4
(3*1)*7	8214	6892	36.3	71	68	174	151	29.2	20.0
(3*1)*8	8661	8005	28.0	71	69	147	124	29.8	21.7
1*(4*6)	7637	8232	30.9	69	69	158	128	27.8	20.5

Table 15. Continued.

	Grain yield kg ha^{-1}		1000-seed weight g	Days to 50% anthesis d		Plant height cm		Panicle length cm	Panicle exsertion cm
Entry	1991	1992	1991	1991	1992	1991	1992	1991	1991
Three-way crosses									
1*(4*7)	7444	8852	33.7	71	70	157	127	27.5	17.1
1*(4*8)	7423	8125	30.1	71	70	144	134	29.1	15.1
2*(3*6)	7368	6895	32.4	71	72	141	140	30.8	14.5
2*(3*8)	8128	5896	30.4	71	71	140	121	32.4	14.6
2*(3*7)	7276	6641	36.2	72	70	168	144	31.4	16.8
2*(4*6)	7506	6334	30.7	71	69	148	126	31.7	14.1
3*(4*7)	9112	6071	30.7	75	73	145	133	29.6	13.1
(2*1)*6	7637	7496	31.5	71	70	159	133	28.7	17.5
(2*1)*8	7444	7929	29.9	71	71	145	143	31.4	17.9
(3*5)*7	8453	5712	38.7	71	71	150	140	31.0	17.4
(3*5)*8	6561	3882	30.0	71	72	135	129	31.8	17.2
Means	7815 ab	6921 a	32.2a	71 b	70 b	151 a	134 a	30.0ab	17.1a
Double crosses									
(2*1)*(3*6)	7910	7653	31.8	71	72	146	139	27.1	17.0
(2*1)*(3*7)	6374	7668	34.1	71	72	164	131	29.5	15.4
(2*1)*(3*8)	8110	6794	31.9	71	71	143	136	30.2	16.9
(2*1)*(4*7)	7058	7187	35.1	71	68	155	120	28.5	17.8
(3*1)*(4*6)	8769	7457	31.4	71	71	139	133	28.5	15.6
(3*1)*(4*8)	7711	7677	29.1	71	71	135	127	29.1	14.6
(3*1)*(4*7)	7699	6941	33.0	72	71	152	144	29.8	14.2
(3*2)*(4*6)	7404	7230	29.9	71	70	136	148	29.2	17.3
(3*2)*(4*8)	6981	6196	29.1	72	70	135	125	31.5	15.0
(3*2)*(4*7)	8030	6997	33.6	71	71	155	129	30.0	12.3
Means	7605 b	7180 a	31.9a	71 b	71 b	146 a	133 a	29.4b	15.6a
General means	7447	6776	31.9	72	71	145	131	29.8	15.6
LSD (0.05)	1627	2263	2.4	2	4	10	23	2.8	5.1

† Parents in a particular cross are identified by number; e.g. 1*2 is a single cross of ATx630 by BTx631, while (3*1)*6 represents a three-way cross of the single cross A_2Tx632 by BTx630, and the parent RTx432; similarly, (2*1)*(3*6) is a double cross involving the single crosses of ATx631 by BTx630, and A_2Tx632 by RTx432.

‡ Type means within the same column followed by the same letter are not significantly different according to LSD (0.05)

to 31.0 cm in a three-way cross, (A_2Tx632*RTx430)*SC103-12E. The hybrids recorded greater panicle length than the parental lines. The single crosses also had longer panicles than the double crosses (Table 15). Panicle exsertion was greater in the hybrids than in the parental lines, with an overall mean of 15.6 cm, ranging from 0.0 cm in RTx430 to 22.6 cm in ATx630*B_2Tx632 Table 15.

The same measurements as those taken at College Station and Halfway were recorded at Corpus Christi in 1991 and 1992 except that at Corpus Christi 1000-seed weight were recorded in both years, while days to 50% anthesis was recorded only in 1991. The analysis of variance mean squares for all characters at Corpus Christi are as shown in Table 16. Highly significant differences were indicated for all the characters studied in both years. Highly significant differences also were indicated for among parents, among single crosses and among three-way crosses. However, among three-way crosses variability for panicle length was significant only at the 0.05 probability level. Among double crosses, statistically nonsignificant differences were indicated in 1991 for grain yield, days to 50% anthesis, and panicle exsertion. The mean of squares attributed to differences among the type groups were significant for all characters indicating presence of variation among types. These sums of squares due to types were partitioned as previously into single-degree-of-freedom contrasts. The parents vs hybrids mean squares were significant for all characters studied in both years. Single crosses vs three-way crosses and double crosses were significant for 1000- seed weight in 1991 and days to 50% anthesis, while three-way crosses vs double crosses were significant for 1000-seed weight and plant height in 1992. The least significant difference test (P=0.05) was used to test for difference among the type-groups. Hybrid-types were found to indicate no significant differences for their mean performances. The hybrid-types uniformly outperformed the parental lines in all the characters in 1991 and 1992 (Table 17).

Grain yield at Corpus Christi ranged from 1060 kg/ha in BTx630 to 9131 kg/ha in the single cross ATx630*SC103-12E in 1991, and from 562 kg/ha in RTx430 to 5413 kg/ha in the single cross ATx631*SC103-12E in 1992 (Table 17). The year means at Corpus Christi were 6181 kg/ha in 1991 and 3727 kg/ha in 1992. The best three-way cross in 1991, (A_2Tx632*BTx630)*SC103-12E, was ranked fifth, whereas the best three-way cross in 1992, (A_2Tx632*RTx430)*SC103-12E, was ranked fourth. In both years the highest yielding three-way was not significantly different (LSD) from the highest yielding cultivar.

The overall cultivars 1000-seed weight means at Corpus Christi were 30.2 g and 26.8 g in 1991 and 1992, respectively. In 1991 1000-seed weight ranged from 22.6 g in BTx630 to 35.2 g in the single cross, A_2Tx632*RTx430. In 1992 the range for 1000-seed weight was 19.8 g in SC103-12E to 31.2 g in the single cross ATx631*RTx430, with a three-way cross, (A_2Tx632*RTx430)*SC103-12E, ranking third (32.8 g) in 1991 and second (30.4 g) in 1992.

Table 16. Estimated mean squares for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Corpus Christi in 1991 and 1992.

		Grain yield kg ha^{-1}		1000-seed weight g		Days to 50% anthesis d	Plant height cm		Panicle length cm	Panicle exsertion cm
Source	df	1991	1992	1991	1992	1991	1991	1992	1991	1991
Replicates	2	*153.24†*	*318.04**†*	0.13	26.36**	0.75	29890.31**	1651.41**	50.08**	90.65**
Entries	51	802.27**	411.68**	17.68**	18.80**	26.68**	558.90**	935.47**	16.97**	46.19**
Parents (P)	7	792.06**	255.37**	20.38**	28.94**	78.71**	968.35**	1414.43**	44.16**	87.15**
SC	18	617.81**	297.19**	11.52**	14.48**	21.97**	292.20**	638.13**	13.46**	37.09**
TWC	14	182.98**	131.32**	6.14**	11.83**	13.36**	386.37**	410.21**	11.07*	16.77**
DC	9	144.47	96.78*	1.95*	6.02**	5.00	210.43**	399.69**	11.15*	10.56
Types	3	6796.29**	3716.43**	149.39**	92.01**	60.86**	3054.24**	5660.51**	19.56*	249.30**
P vs hybrids	1	20297.46**	11096.84**	438.48**	255.13**	142.37**	9042.40**	16809.05**	46.29**	693.93**
SC vs (TWC+DC)	1	86.33	14.03	8.85**	2.99	38.81**	17.50	0.00	11.42	15.26
TWC vs DC	1	74.88	38.43	0.85	17.92**	1.39	102.82	172.48*	0.98	38.72*
Error	102	75.11	40.13	0.99	1.79	3.37	31.64	41.93	5.12	6.37
CV %		14.01	17.00	3.29	4.98	2.44	4.91	4.81	8.39	16.62

† Mean squares equal 10^4 times the column values.
*, ** Significant at 0.05 and 0.01 probability levels, respectively.

Table 17. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Corpus Christi in 1991 and 1992.

	Grain yield kg ha^{-1}		1000-seed weight g		Days to 50% anthesis d	Plant height cm		Panicle length cm	Panicle exsertion cm
Entry†	1991	1992	1991	1992	1991	1991	1992	1991	1991
Parents									
1 BTx630	1060	878	22.6	22.2	81	124	148	27.6	12.7
2 BTx631	2461	662	27.2	26.3	82	123	137	30.7	7.4
3 B_2Tx632	4855	2099	28.2	25.0	77	92	109	25.2	15.7
4 B_2Tx636	3996	3065	24.7	21.7	76	89	100	23.9	6.4
5 RTx430	1425	562	29.1	28.9	83	98	101	27.5	-0.4
6 RTx432	4709	2307	29.3	25.5	76	91	110	23.8	12.9
7 SC103-12E	5141	2301	25.3	19.8	67	73	82	18.2	14.2
8 SC599-11E	4453	2121	23.3	21.0	76	84	96	28.6	13.0
Means	3513 b‡	1749 b	26.2b	23.8b	77 a	97 b	110 b	25.7b	10.2b
Single crosses									
1*2	3131	950	30.8	25.7	79	124	149	29.7	8.0
1*3	7286	4333	31.0	28.9	75	126	153	25.7	18.3
1*4	6817	4630	29.3	26.5	75	118	142	27.7	13.5
1*6	6268	3425	31.9	27.8	74	131	164	25.8	19.0
1*7	9131	5181	31.5	30.0	73	136	164	26.7	24.6
1*8	7688	5014	27.7	24.7	74	120	148	29.1	17.6
2*3	7182	3572	32.3	27.3	77	113	132	28.0	15.3
2*4	5556	3799	28.5	24.7	75	111	136	29.1	15.3
2*5	5793	2758	30.1	31.2	79	122	136	33.2	10.8
2*6	5860	3874	31.8	27.0	77	127	155	26.8	16.7
2*7	8504	5413	29.1	28.5	72	129	156	27.8	21.3
2*8	6786	3481	26.9	24.0	76	115	137	29.7	15.9
3*5	6524	4596	35.2	30.0	74	112	121	26.9	14.9
3*6	6433	4289	33.0	29.4	72	106	133	23.9	18.2
3*7	8906	4156	31.3	28.4	69	118	128	27.5	16.4
3*8	6743	3968	30.5	25.2	71	102	121	27.9	17.1
4*6	5336	4328	31.0	26.9	73	107	123	24.7	16.9
4*7	8553	4552	29.9	26.5	70	117	132	25.4	17.1
4*8	6073	4621	28.8	23.5	72	100	116	28.1	16.0
Means	6767 a	4050 a	30.6a	27.2a	74 b	117 ab	139 a	27.6a	16.5a
Three-way crosses									
(3*1)*6	6743	4228	31.3	28.1	73	117	151	25.2	18.0
(3*1)*7	8145	4854	31.7	29.4	71	116	143	24.9	20.3
(3*1)*8	6439	4372	29.6	24.9	74	111	130	27.9	18.6
1*(4*6)	5921	3633	30.8	26.3	77	125	147	26.5	15.5
1*(4*7)	7371	4511	32.2	28.3	75	148	165	26.6	19.2

Table 17. Continued.

	Grain yield kg ha^{-1}		1000-seed weight g		Days to 50% anthesis d	Plant height cm		Panicle length cm	Panicle exsertion cm
Entry†	1991	1992	1991	1992	1991	1991	1992	1991	1991
Three-way crosses									
1*(4*8)	6774	4184	28.9	24.3	77	117	139	26.5	18.3
2*(3*6)	6329	2606	32.3	26.6	77	117	140	25.3	16.2
2*(3*8)	4892	3079	31.0	27.4	77	113	136	29.5	12.8
2*(3*7)	7371	4405	30.9	30.1	77	138	151	29.4	14.3
2*(4*6)	5848	3802	31.5	26.5	77	116	143	26.9	13.4
3*(4*7)	6427	3539	30.6	26.0	74	113	126	25.6	14.3
(2*1)*6	6512	3910	31.8	28.1	76	127	150	24.7	17.1
(2*1)*8	7054	4854	27.4	24.1	74	115	138	27.1	18.3
(3*5)*7	7310	4937	32.8	30.4	71	115	131	28.3	15.8
(3*5)*8	6238	3940	32.1	25.6	75	101	118	31.3	13.6
Means	6625 a	4057 a	31.0a	27.1a	75 b	119 a	140 a	27.1ab	16.4a
Double crosses									
(2*1)*(3*6)	5720	3973	32.3	29.2	75	109	154	23.2	17.6
(2*1)*(3*7)	7188	4422	31.1	29.4	76	126	144	24.4	16.3
(2*1)*(3*8)	6104	4001	30.3	26.2	74	116	139	27.2	15.2
(2*1)*(4*7)	7712	4646	31.2	28.6	75	130	152	27.6	17.3
(3*1)*(4*6)	6585	4488	31.9	28.6	73	117	131	26.4	14.8
(3*1)*(4*8)	6293	4619	30.3	25.7	75	107	123	27.2	12.7
(3*1)*(4*7)	6073	4837	31.2	29.1	78	125	139	29.6	12.1
(3*2)*(4*6)	6159	3539	32.1	28.0	77	110	127	28.1	14.0
(3*2)*(4*8)	6256	3024	30.0	26.5	76	108	121	28.7	13.4
(3*2)*(4*7)	7627	4480	31.7	29.4	77	120	142	25.8	15.7
Means	6572 a	4203 a	31.2a	28.1a	75 b	117 a	137 a	26.8ab	14.9a
General means	6188	3727	30.2	26.8	75	116	135	27.0	15.2
LSD (0.05)	1404	1026	1.6	2.2	3	9	11	3.7	4.1

† Parents in a particular cross are identified by number; e.g. 1*2 is a single cross of ATx630 by BTx631, while (3*1)*6 represents a three-way cross of the single cross A_2Tx632 by BTx630, and the parent RTx432; similarly, (2*1)*(3*6) is a double cross involving the single crosses of ATx631 by BTx630, and A_2Tx632 by RTx432.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

Days to 50 % anthesis at Corpus Christi in 1991 ranged from 67 d in SC103-12E to 83 d in RTx430, with an overall cultivars mean of 75 d. The ranges in plant height during 1991 were 73 cm in SC103-12E to 148 cm in the three-way cross, ATx630*(A_2Tx636*SC103-12E, and 82 to 165 cm in the same cultivars during 1992. The overall cultivars means for plant height were 117 cm and 137 cm in 1991 and 1992, respectively. The mean panicle length overall cultivars was 27 cm, ranging from 18.2 cm in the parental line SC103-12E to 33.2 cm in the single cross, ATx631*RTx430. A three-way cross (A_2Tx632*RTx430)*SC599-11E ranked second in panicle length. Panicle exsertion ranged from -0.4 cm in RTx430 to 24.6 cm in ATx630*SC103-11E.

The estimated mean squares for agronomic characters at Chillicothe in 1991 and 1992 are presented in Table 18. Days to 50% anthesis were not recorded at this location whereas 1000-seed weight, panicle length, and panicle exsertion were measured only in 1991. Grain yield and plant height data were recorded in both the years.

Highly significant differences were indicated among the entries, an indication of considerable cultivar differences for each of the characters studied. The sum of squares due to entries were partitioned into variations among cultivars within type-groups and among the type-groups. The variability among the parental lines was significant for all the characters. Among single crosses mean squares were highly significant for all the characters except panicle length. Highly significant differences were indicated among the three-way cross cultivars, and among the double crosses for plant height in both years, and 1000-seed weight (Table 18). The mean squares due to types were highly significant in all the characters. The variability among types was further partitioned into sources attributable to differences among the type-groups (Table 18). Parents vs hybrids were highly significant for all the characters. Single crosses vs three-way crosses and double crosses combined were significant for grain yield in 1992 and 1000-seed weight. Three-way crosses vs double crosses were significant for all the characters except panicle length and grain yield in 1991.

The means for the characters studied at Chillicothe during 1991 and 1992 are given in Table 19. Except for panicle exsertion in the double crosses, each of the hybrid-types differed significantly (LSD; P=0.05) from the parental lines in the characters studied. Three-way crosses indicated significantly higher 1000-seed weight and panicle exsertion than the single crosses, and grain yield in 1992 and, plant height and panicle exsertion in 1991, than the double crosses. Single crosses indicated significantly higher grain yield in 1992 and 1000-seed weight than the double crosses.

Grain yields were higher in 1992 than in 1991, with overall cultivars means of 3238 kg/ha and 6139 kg/ha, respectively. The ranges in grain yield were from 910 kg/ha, in RTx430, to 4463 kg/ha, in a double cross (ATx631*BTx630)*(A_2Tx636*SC103-12E) in 1991, and 1080 kg/ha,

Table 18. Estimated mean squares for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Chillicothe in 1991 and 1992.

Source	df	Grain yield $kg\ ha^{-1}$ 1991	Grain yield $kg\ ha^{-1}$ 1992	1000-seed weight g 1991	Plant height cm 1991	Plant height cm 1992	Panicle length cm 1991	Panicle exsertion cm 1991
Replicates	2	70.61†	15533.79**†	0.77	35.02	40.69	77.54**	72.06*
Entries	51	198.74**	602.03**	19.84**	1279.63**	579.79**	49.39**	51.64**
Parents (P)	7	112.41**	300.14**	24.49**	1119.07**	829.91**	145.48**	44.11*
SC	18	77.06**	182.84**	14.94**	697.20**	267.86**	21.66	67.29**
TWC	14	45.56	129.47	17.89**	524.49**	228.39**	10.49	27.31
DC	9	49.24	129.23	7.18**	516.75**	232.38**	14.51	23.12
Types	3	2293.59**	7445.30**	85.42**	10961.41**	4549.90**	277.82**	174.46**
P vs hybrids	1	6742.09**	21083.81**	124.99**	31764.13**	13308.06**	782.89**	301.66**
SC vs (TWC+DC)	1	59.39	461.37*	117.62**	31.73	134.63	23.08	27.56
TWC vs DC	1	79.30	790.72**	13.65**	1088.37**	206.99*	27.50	194.16**
Error	102	26.84	86.61	1.28	85.47	41.25	12.93	17.71
CV %		16.00	15.16	3.63	6.25	5.20	12.99	39.03

† Mean squares equal 10^4 times the column values.
*, ** Significant at 0.05 and 0.01 probability levels, respectively.

Table 19. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at Chillicothe in 1991 and 1992.

	Grain yield kg ha^{-1}		1000-seed weight g	Plant height cm		Panicle length cm	Panicle exsertion cm
Entry†	1991	1992	1991	1991	1992	1991	1991
Parents							
1 BTx630	1824	3126	27.7	132	138	27.3	6.7
2 BTx631	2187	3929	29.5	123	110	25.7	3.3
3 B2Tx632	1284	3733	31.6	105	98	22.5	11.2
4 B_2Tx636	2514	3777	26.6	105	97	26.3	2.0
5 RTx430	911	1080	32.8	91	95	23.2	4.8
6 RTx432	1406	3788	31.4	99	103	23.7	9.3
7 SC103-12E	1079	4317	27.9	70	81	19.4	11.3
8 SC599-11E	2363	3553	24.4	92	93	25.0	11.5
Means	1696 b‡	3413 c	29.0c	102 c	102 b	24.1b	7.5c
Single crosses							
1*2	2522	5948	34.7	127	123	32.3	5.8
1*3	3173	5898	30.2	148	128	27.3	13.5
1*4	3585	6178	30.0	135	128	27.7	8.5
1*6	3813	6601	33.5	148	136	25.2	16.0
1*7	4359	8185	31.2	192	150	28.8	18.3
1*8	4076	6958	28.1	150	136	31.0	14.7
2*3	2900	6792	28.1	134	117	33.8	10.3
2*4	3326	7016	29.0	128	118	30.8	6.3
2*5	2594	6986	30.0	137	127	33.5	2.3
2*6	4136	7011	31.4	156	133	29.5	7.0
2*7	3158	7454	33.1	146	136	32.8	9.5
2*8	3883	7077	29.9	139	129	27.8	14.8
3*5	3375	7124	27.8	130	115	28.0	10.5
3*6	3297	5574	27.8	146	118	26.8	18.5
3*7	3456	8448	33.4	140	129	29.0	5.8
3*8	2850	6845	28.4	131	119	24.5	17.7
4*6	3460	5582	29.9	124	114	26.7	8.7
4*7	3687	7615	32.9	142	130	28.0	8.3
4*8	3731	6845	27.9	130	116	29.3	9.5
Means	3441 a	6849 a	30.4b	141 ab	126 a	29.1a	10.9b
Three-way crosses							
(3*1)*6	3802	6853	30.7	145	132	24.8	14.4
(3*1)*7	4227	8418	32.7	177	145	29.1	15.3
(3*1)*8	3326	6726	28.5	145	123	26.7	19.8
1*(4*6)	2993	6441	31.4	150	132	24.7	13.4
1*(4*7)	3440	6706	33.9	162	149	26.4	16.4
1*(4*8)	3400	6133	29.3	138	125	26.5	12.3

Table 19. Continued.

	Grain yield kg ha⁻¹		1000-seed weight g	Plant heigh cm		Panicle lengtht cm	Panicle exsertion cm
Entry†	1991	1992	1991	1991	1992	1991	1991
Three-way crosses							
2*(3*6)	4059	5881	31.4	138	125	27.1	15.0
2*(3*8)	3963	6629	31.8	128	120	28.9	9.2
2*(3*7)	3744	7451	34.7	146	128	30.1	14.1
2*(4*6)	4194	7352	31.1	137	128	30.0	7.2
3*(4*7)	2992	6216	33.0	157	134	28.3	11.5
(2*1)*6	3938	6369	31.1	145	133	26.8	12.6
(2*1)*8	3612	6956	29.5	133	127	28.0	10.8
(3*5)*7	3745	6969	38.4	149	131	31.0	11.8
(3*5)*8	3469	5956	31.6	127	115	28.2	12.6
Means	3660 a	6737 a	32.0a	145 a	130 a	27.8a	13.1a
Double crosses							
(2*1)*(3*6)	3331	6382	32.6	144	129	29.3	10.7
(2*1)*(3*7)	3443	6405	32.3	154	134	29.3	6.8
(2*1)*(3*8)	3230	6867	31.0	136	128	26.0	14.9
(2*1)*(4*7)	4463	7147	34.4	151	136	29.3	9.3
(3*1)*(4*6)	3032	5801	31.5	126	119	28.7	11.1
(3*1)*(4*8)	3456	6081	31.9	122	116	24.4	12.8
(3*1)*(4*7)	3636	5674	35.3	149	138	31.3	10.2
(3*2)*(4*6)	3034	6058	32.9	130	118	30.3	9.0
(3*2)*(4*8)	3388	5131	31.3	116	115	31.0	5.9
(3*2)*(4*7)	3493	5197	34.9	146	131	30.4	7.3
Means	3451 a	6074 b	32.8a	137 b	126 a	29.0a	9.8bc
General means	3238	6139	31.1	136	124	28.0	10.8
LSD (0.05)	839	1507	1.8	15.0	10.4	5.8	6.8

† Parents in a particular cross are identified by number; e.g. 1*2 is a single cross of ATx630 by BTx631, while (3*1)*6 represents a three-way cross of the single cross A_2Tx632 by BTx630, and the parent RTx432; similarly, (2*1)*(3*6) is a double cross involving the single crosses of ATx631 by BTx630, and A_2Tx632 by RTx432.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05)

in RTx430, to 8448 kg/ha, in the single cross A_2Tx632*SC103-12E in 1992. A three-way cross (A_2Tx632*BTx630)*SC103-12E was third ranking in 1991 (4227 kg/ha) and second ranking in 1992 (8418 kg/ha), while changing ranks with a single cross ATx630*SC103-12E in both years. 1000-seed weight ranged from 24.4 g in SC599-11E to 38.4 g in the three-way cross (A_2Tx632*RTx430)*SC103-12E. The 1000-seed weight overall cultivars mean was 31.1 g.

Plant height ranged from 70 to 192 cm in 1991, with a mean of 136 cm, and ranged from 81 to 150 cm in 1992, with a mean of 124 cm. The shortest cultivar was SC103-12E while the tallest was a single cross, ATx630*SC103-12E, in both years. Two three-way crosses, (A_2Tx632*BTx630)*SC103-12E and ATx630*(A_2Tx636*SC103-12E) interchanged the second and third ranks in 1991 and 1992, respectively. Panicle length varied significantly from 19.4 cm, in SC103-12E, to 33.8 cm, in the single cross ATx631*B_2Tx632. The overall cultivars mean for panicle length at Chillicothe in 1991 was 28.0 cm. Panicle exsertion had a mean of 10.8 cm, ranging from 2.0 cm, in B_2Tx636 to 19.8 cm in the three-way cross (A_2Tx632*BTx630)*SC599-11E.

Combined Analysis for Texas Trials in 1991 and 1992

The individual location-year combinations were considered distinct environments for the combined analysis of variance and the stability analysis (Table 20). The environmental mean yields of all entries ranged from 3238 kg/ha at Chillicothe in 1991 to 7447 kg/ha at Halfway in 1991, with mean yields for the other environments tending towards the lower or higher portion between these limits. Mean 1000-seed weight ranged from 26.8 to 31.9 g, days to anthesis from 71 to 76 d, plant height from 116 to 145 cm, panicle length from 27.0 to 27.2 cm, and mean panicle exsertion from 10.8 to 18.0 cm.

Overall environments, the mean grain yield was 3007 kg/ha for parental lines, 5740 kg/ha for single crosses, 5508 kg/ha in three-way crosses and 5377 kg/ha in double crosses (Table 21.). The type means for 1000-seed weight were 27.6 g in parental lines, 30.4 g in single crosses, 30.7 g in three-way hybrids, and 31.2 g in double crosses, mean plant heights were 109 cm parental lines, 135 cm single crosses, 136 three-way crosses, and 133 cm double crosses; mean days to 50% anthesis were 77 d in parental lines and 73 d in single, three-way and double cross hybrids. Panicle length means were 25.8 cm in parental lines, 28.9 cm in single crosses and 28.0 cm in three-way and double crosses, panicle exsertion type means were 9.8 cm in parental lines, 15.8 cm in single crosses, 16.7 cm in three-way crosses and 14.7 cm in double crosses.

A single cross was the highest yielding entry in five environments, a three-way cross hybrid in two, and a double cross in one of the eight environments. Two single crosses ATx631*Sc103-12E and A_2Tx632*SC103-12E, each ranked highest in grain yield in two different environments.

Table 20. Mean squares in the combined analysis of variance for agronomic characters of sorghum parents, single, three-way, and double cross hybrids when stability parameters are estimated in Texas 1991 and 1992.

Source	df	Mean Squares: Grain yield	Mean Squares: Grain yield	Mean Squares: Plant height	df	Mean Squares: 1000-seeds weight	Mean Squares: Days to 50% anthesis	df	Mean Squares: Panicle length	Mean Squares: Panicle exsertion
		kg ha^{-1}†	$\log_{10}$	cm		g	d		cm	cm
Environments (Env)	7	13777.71**	1.175**	4061.26**	4	207.45**	236.93**	3	89.10**	473.37**
Replicates/Env	16	376.81	0.038	1354.65	10	3.00	10.45	8	11.68	19.15**
Entries	53	981.47**	0.186**	1571.43**	51	23.28**	29.21**	51	23.02**	58.79**
Among Parents(P)	7	608.07**	0.360**	1881.62**	7	33.03**	94.11**	7	66.66**	90.61**
Among Single Crosses(SC)	18	355.32**	0.732**	874.56**	18	15.33**	17.60**	18	14.41**	52.87**
Among Three-way Crosses(TWC)	14	145.93**	0.013	574.07**	14	19.89**	4.90	14	8.75**	17.91**
Among Double Crosses(DC)	9	85.86	0.007	563.14**	9	6.45*	2.12	9	4.55	7.85
Types	3	12195.73**	1.987**	12708.07**	3	114.57**	142.06**	3	94.91**	363.62**
P vs H	1	35808.70**	5.940**	37627.87**	1	320.20**	420.56**	1	250.13**	997.07**
SC vs (TWC+DC)	1	696.46**	0.019	0.02	1	15.22*	4.89	1	33.95**	0.16
TWC vs DC	1	82.05	0.003	496.33**	1	8.30	0.73	1	0.15	93.63**
Entries X Env	357	67.08**	0.011**	66.05**	204	2.67**	5.23**	153	3.14**	5.88**
Among P X Env	49	66.37**	0.032**	76.92**	28	2.19**	11.75**	21	7.74**	9.67**
Among SC X Env	126	72.74**	0.997**	53.83**	72	3.77**	5.43**	54	1.91	6.94**
Among TWC X Env	98	66.31**	0.007	53.34**	56	1.43**	2.86**	42	1.19	2.70
Among DC X Env	63	33.18	0.005	48.96**	36	1.09**	1.78	27	2.02	3.00
Type X Env	21	140.17**	0.015**	224.53**	12	7.79**	10.34**	9	12.19	14.18**
P vs H X Env	7	257.49**	0.027**	571.27**	4	14.52**	22.09**	3	32.00**	33.18**
SC vs (TWC+DC) X Env	7	114.22**	0.013*	72.62**	4	7.17**	7.45**	3	0.65	4.75
TWC vs DC X Env	7	52.13	0.005	29.71	4	1.71**	1.49	3	3.89	4.61

Table 20. Continued.

Source	df	Mean Squares: Grain yield	Mean Squares: Grain yield	Mean Squares: Plant height	df	Mean Squares: 1000-seed weight	Mean Squares: Days to 50% anthesis	df	Mean Squares: Panicle length	Mean Squares: Panicle exsertion
		kg ha^{-1}†	$\log_{10}$	cm		g	d		cm	cm
Env(*l*)	1	96443.94**	8.224**	28428.83**	1	829.82**	947.72**	1	267.35**	1420.12**
Entries X Env(*l*)	51	84.58	0.008	41.33	51	1.83	6.86	51	1.03	7.69*
Among P X Env(*l*)	7	55.26	0.007	17.63	7	2.56	24.94**	7	1.58	12.74**
Among SC X Env(*l*)	18	68.70	0.009	28.58	18	2.35	6.72	18	1.22	6.22
Among TWC X Env(*l*)	14	60.29	0.006	41.83	14	1.01	2.77	14	0.67	2.80
Among DC X Env(*l*)	9	20.00	0.003	22.52	9	0.54	0.93	9	0.59	5.87
Type X Env(*l*)	3	555.31**	0.029*	227.20*	3	4.63	2.29	3	1.52	32.94**
P vs H X Env(*l*)	1	1501.07**	0.078**	603.93**	1	11.53*	1.70	1	1.35	81.48**
SC vs (TWC+DC) X Env(*l*)	1	164.29	0.014	48.75	1	0.31	5.18	1	1.48	6.88
TWC vs DC X Env(*l*)	1	0.36	0.009	28.95	1	2.05	0.00	1	1.72	10.46
Pooled deviations	312	62.93*	0.011**	68.82**	156	2.90**	4.60**	104	4.11**	4.61
Parents	48	65.00**	0.033**	135.80**	24	3.47**	9.49**	16	14.47**	8.07**
SC	114	72.17**	0.008*	60.06**	57	4.38**	4.86**	38	2.32	7.01**
TWC	90	67.36**	0.007	57.25**	45	1.61**	2.97**	30	1.36	2.80
DC	60	37.10	0.005	49.23**	30	1.58**	2.65*	20	3.37*	1.42
Pooled error	816	34.42	0.005	23.75	510	0.52	1.51	408	2.09	3.60
CV%		19.61	3.34	6.45		4.13	2.89		8.97	22.04

† Mean squares equal 10^4 times the column values.

*, ** Significant at .05 and .01 probability levels, respectively.

These results, however, were obtained with hybrids developed from a selected group of lines. If lines are derived, instead, from a random mating population and, if epistasis is not important in the expression of yield, it should always be possible to obtain a single cross that will outyield any of the three-way crosses derived from the same set of lines. This superiority is due to a larger variance among single crosses than among three-way crosses, as pointed out by Cockerham (1961).

Significant differences ($P \leq 0.01$) were indicated for the environments and entries sources of variation, and for the entries X environment interactions (Table 20). This indicated appreciable variation in the environments covered and the cultivars included in the experiment, for these characters. The occurrence of significant entries X environment interactions allows for the evaluation of the cultivars for stability of performance across different environments.

Partitioning of the entries sums of squares for the characters into orthogonal comparisons among groups, and among entries within groups showed that the differences in grain yield, and panicle length were significant among all types except for among double crosses, and the three-way hybrids vs double crosses comparison. Differences in plant height were significant in all except the single crosses vs three-way crosses and double crosses contrast. 1000-seed weight was not significant except only for the contrast three-way crosses vs double crosses. Days to 50% anthesis was not significantly different among three-way crosses, among double crosses, and for the contrasts single crosses vs three-way crosses and double crosses combined, and three-way crosses vs double crosses. The variability in panicle exsertion was not significant among double crosses and, for the single crosses vs three-way crosses and double-crosses combined orthogonal contrast.

The mean squares from the conventional analysis of variance for the interactions of the different type-groups with environments were highly significant for all the type-groups in plant height and 1000-seed weight. The mean squares for among double crosses X environments were not significant for grain yield and days to 50% anthesis. In the case of panicle length only the interaction among parents X environments was significant. Interactions among three-way crosses and among double crosses with environments were not significant for panicle exsertion. The interactions mean squares for the individual orthogonal comparisons indicated high significance for all characters in the contrast parents vs hybrids. The contrast single crosses vs three-way crosses and double crosses interaction with environments were significant for all the characters except panicle length and panicle exsertion, whereas three-way crosses vs double crosses X environments were significant only for 1000-seed weight.

Table 21. Means for agronomic characters in sorghum parents, single, three-way, and double-cross hybrids at various locations in Texas in 1991 and 1992.

Entry†	Grain yield	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	$kg\ ha^{-1}$	g	d	cm	cm	cm
Parents						
1 BTx630	2606	25.9	80	136	28.3	10.9
2 BTx631	3108	28.7	78	126	29.4	7.5
3 B_2Tx632	3038	29.0	82	106	23.3	15.8
4 B_2Tx636	3889	25.3	75	103	25.7	7.0
5 RTx430	1070	31.5	80	104	28.4	-1.0
6 RTx432	3486	29.9	74	109	23.9	11.3
7 SC103-12E	3558	26.6	69	88	20.2	11.4
8 SC599-11E	3301	23.9	74	97	27.1	0.4
Means	3007 c‡	27.6c	77 a	109 c	25.8c	9.8c
Single crosses						
1*2	3639	31.0	78	136	30.4	8.7
1*3	5685	30.8	75	141	27.1	18.2
1*4	5522	28.6	73	133	28.0	13.6
1*6	5162	31.4	74	149	26.5	18.9
1*7	6335	33.1	70	161	28.8	20.4
1*8	6449	28.1	73	140	29.8	18.6
2*3	5410	30.9	75	128	30.3	16.0
2*4	5675	28.1	73	127	30.8	12.1
2*5	5265	31.7	75	134	33.6	8.0
2*6	5955	30.7	74	145	28.4	14.9
2*7	6583	32.1	71	147	30.8	17.9
2*8	6104	28.1	73	136	30.4	16.8
3*5	5984	32.1	75	125	28.9	14.3
3*6	5553	31.6	74	129	26.2	21.5
3*7	6436	32.9	72	134	27.6	13.4
3*8	5560	28.9	73	121	27.7	19.7
4*6	5407	29.4	72	123	26.2	15.8
4*7	6272	30.7	71	136	27.9	16.3
4*8	6065	27.5	72	120	29.2	15.1
Means	5740 a	30.4b	73 b	135 ab	28.9a	15.8a
Three-way crosses						
(3*1)*6	5937	31.0	72	139	25.9	19.1
(3*1)*7	6276	32.7	71	150	27.1	19.6
(3*1)*8	5797	27.9	73	130	27.8	20.7
1*(4*6)	5271	29.6	73	138	26.0	16.7
1*(4*7)	5592	31.9	72	150	26.5	18.1
1*(4*8)	5414	28.1	73	131	27.3	16.0

Table 21. Continued.

Entry†	Grain yield	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	g	d	cm	cm	cm
Three-way crosses						
2*(3*6)	5285	31.0	74	135	27.4	16.7
2*(3*8)	5123	30.5	74	127	30.0	13.5
2*(3*7)	5491	33.0	73	147	29.6	16.7
2*(4*6)	5481	30.2	73	134	29.2	13.1
3*(4*7)	5014	30.7	75	134	27.3	14.5
(2*1)*6	5826	30.5	73	143	26.8	16.4
(2*1)*8	5919	28.0	74	133	28.9	17.0
(3*5)*7	5635	35.3	72	135	29.5	16.2
(3*5)*8	4561	30.4	73	119	30.4	15.7
Means	5508 b	30.7b	73 b	136 a	28.0b	16.7a
Double crosses						
(2*1)*(3*6)	5329	31.8	74	136	26.5	16.7
(2*1)*(3*7)	5306	32.0	73	143	27.6	14.5
(2*1)*(3*8)	5470	29.9	74	132	27.7	16.6
(2*1)*(4*7)	6001	32.5	72	145	28.0	16.1
(3*1)*(4*6)	5654	31.0	73	128	27.2	14.9
(3*1)*(4*8)	5226	29.5	73	122	27.1	14.2
(3*1)*(4*7)	5199	32.2	74	139	29.7	13.1
(3*2)*(4*6)	5164	31.3	72	128	28.5	14.6
(3*2)*(4*8)	4807	29.9	73	121	29.8	13.0
(3*2)*(4*7)	5618	32.4	74	136	28.4	13.2
Means	5377 b	31.2a	73 b	133 b	28.0b	14.7b
General means	5183	30.2	74	131	28.0	14.9
LSD (0.05)	576	0.9	2	5	2.0	2.6

† Parents in a particular cross are identified by number; e.g. 1*2 is a single cross of ATx630 by BTx631, while (3*1)*6 represents a three-way cross of the single cross A_2Tx632 by BTx630, and the parent RTx432; similarly, (2*1)*(3*6) is a double cross involving the single crosses of ATx631 by BTx630 and A_2Tx632 by RTx432.

‡ Type means within the same column followed by same letter are not significantly different according to LSD (0.05).

Stability Analysis of Texas Trials 1991 and 1992

The conventional combined analysis of variance over environments provides information on cultivar-environment interactions, but gives no measurement of stability of the individual cultivars or types of related entries. Most plant breeding programs aim at selecting cultivars that are consistently high-yielding over the range of environments that occur in different locations or seasons. However, the failure of cultivars to have the same relative performance in different environments due to differences in relative rankings (Eberhart and Russell, 1966) reduces efficiency in selection. Comstock and Moll (1963) have shown statistically the effect of large cultivar-environment interactions in reducing progress from selection. The stability analysis of data, as proposed by Finlay and Wilkinson (1963) and, Eberhart and Russell (1966), provides all those parameters that are needed to measure the dependability of each cultivar in each environment.

The stability analysis, through regression of cultivar mean on an environmental index, partitions the GE interactions into two parameters, a regression coefficient (b_i) or slope that indicates the response of a cultivar to differences among environments, and the deviations from regression, to determine if the GE interactions are a linear function of the environmental effects. This is a test to determine if differential responses of the cultivars to environments is explained as a linear function of improvement in the environment mean yields. Significant differences among slopes or regression coefficients indicate that each cultivar has its own specific linear response to a change in environment, while significant deviations from regression indicate nonlinear responses and include that part of cultivar X environment interactions that is unexplainable by additive environmental effects.

The combined regression analysis (Table 20) showed highly significant means of squares for environments (linear) for all the characters, indicating that a large and highly significant proportion of the total environmental and GE interaction variation was attributable to differences between environments (linear). Significant entries X environments (linear) mean squares were indicated only for panicle length implying that the cultivars responded differently to the various environments for this character. The lack of significant (linear) GE interactions for all the other characters in the present study indicated that the cultivars did not differ in their responses to environments.

Significant differences were indicated among slopes of parental lines for days to 50% anthesis and panicle exsertion, but no significant differences were indicated among slopes of the hybrid-types for any of the characters studied. Hybrids differed from the parental lines in their response to environments for grain yield, 1000-seed weight, plant height, and panicle exsertion as is evident from the significant differences in slopes [P vs H X Env(l)] in Table 20. The hybrid types did not differ from each other for all the characters in their responses to environments as is evident from lack of significant differences in their mean slopes.

The pooled deviation mean squares for all the characters except panicle exsertion, were significant when tested against the pooled experimental error, indicating that a high degree of non-linearity existed in the entry/environment relationship. The differences in deviations from regression were highly significant among parental lines for all the characters. The deviations from regression for single crosses were not significant for panicle length only, whereas the deviations for three-way crosses were not significant for panicle length and panicle exsertion. Double cross deviations from regression were not significant for grain yield and panicle exsertion. Generally, double crosses indicated lower deviation mean squares for all the characters in most of the characters followed by three-way crosses, single crosses, and the parental lines showing larger deviations.

This is evidence of stability increasing from parental lines as the unstable type, to single crosses, to three-way hybrids, and to double crosses as the most stable. This supports the previous reports in sorghum (Kofoid et al., 1978; Patanothai and Atkins, 1974a; Reich and Atkins, 1970) that stability increased with an increase in levels of heterogeneity. Jowett (1972) reported that among single crosses, three-way crosses, and parental lines of sorghum, hybrids were more stable than lines. Also, there was some indication of a greater stability among three-way crosses, which would be attributed to population buffering as discussed by Allard and Bradshaw (1964). Ross (1969) also reported variances of three-way cross hybrids to be lower than those in single crosses, indicating three-way crosses to be more stable.

Jowett (1972) and Faris et al. (1981) found that transformation of their yield data from the arithmetic scale to a logarithmic scale improved the stability analysis for grain yield when very wide differences were obtained in yielding ability among entries. The low yielding entries might be constrained by the additive nature of the model on the arithmetic scale. On the arithmetic scale the parental lines do not show larger values of S^2_{di}, or in fact show significantly smaller values. A transformation of the grain yield data in this study was performed to $\log_{10}$, and this resulted in significant changes in the deviation mean squares (Table 20). The parental lines now indicated highly significant deviation mean squares, indicating them to be the most unstable of the four type-groups. The deviation mean squares for single crosses were significant at 0.05 probability level whereas the three-way crosses and double crosses deviations were not significant.

Yield stability of a cultivar is evaluated from estimates of stability parameters. A desirable, stable cultivar is one having mean yield higher than the average yield of all the cultivars under test, regression coefficient close to unity, and small deviations from regression possibly close to zero (Eberhart and Russell, 1966). The mean square for deviations from regression measures the predictability of cultivar reaction to environments. Therefore, this parameter has been regarded as the most appropriate criterion of stability in an agronomic sense (Becker et al., 1982; Becker, 1981; Joppa et al., 1971; Paroda and Hays, 1971; Samuel et al., 1970). The b_i value should better be treated as an indication of the type of response a cultivar is expected to show to varying environments rather than a measure of stability. For example, a cultivar with a high mean performance and b_i value higher than 1.0 would indicate that it is expected to respond with high yields to favorable environmental conditions.Such a cultivar, therefore, can take advantage of the best agronomic treatments that can be applied or the best growing season. On the other hand, a cultivar with a high average performance but with a b_i value lower than 1.0 can be recommended for less favorable environments. Such cultivars can not be ignored simply because their b_i value is not equal to 1.0. However, a cultivar with the b_i value equal to unity can be used with success in a wide range of environments if it, in addition, shows high mean performance. Becker (1981) found the regression coefficient, b_i, to be closely correlated with the environmental variance.

The stability parameters estimated to evaluate relative stability of the cultivars in this study and the different types over a range of environmental conditions are presented in Table 22. The results indicated two parental lines, 10 single crosses, and four each of three-way crosses and double crosses to be unstable for grain yield on the arithmetic scale. When grain yield was transformed to the logarithmic scale, five parental lines, four single crosses and two three-way crosses were categorized unstable, whereas none of the double crosses were unstable. Similar trends were observed for the other characters confirming that more heterogeneous hybrids exhibit greater stability than a less heterogeneous one due to their better buffering capacity.

For special mention among the three-way crosses is (A_2Tx632*ATx630)*SC103-11E. This cultivar performed well across the environments, had a high mean yield overall the environments and indicated b_i = 1.03, with the mean squares due to deviations from regression, S^2_{di}, close to zero. This three-way cross therefore is promising because of its high yield and stability. According to Becker et al. (1982) selection of hybrids with high and stable yield was regarded to be more promising among three-way crosses than among double crosses in winter rye. Yue et al. (1990) suggested that high yield and stability were not mutually exclusive, so that sorghum hybrids with high yield potential and high stability can be identified and selected.

Table 22. Stability parameters for agronomic traits in sorghum parents, single, three-way, and double cross hybrids in eight environments in Texas 1991 and 1992.

Entry†	Grain yield		Log_{10} yield		1000-Seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
Parents														
1 BTx630	0.79	105.70**	1.28	0.052**	1.50	10.50*	1.62	32.90**	0.66	29.50*	0.53	-1.30	0.68	4.80
2 BTx631	0.75	74.61**	1.43	0.070**	0.86	0.76	1.58	10.06**	0.57	39.43*	0.95	6.78	0.74	7.77*
3 B_2BTx632	0.72	18.48	1.22	0.019**	1.22	0.77	-0.98*	5.65	0.91	30.99*	0.38	2.40	1.23	-2.53
4 B_2Tx636	0.83	28.25	1.05	0.005	1.04	0.30	2.08	6.50*	0.87	25.63	0.83	-1.18	0.88	14.94**
5 RTx430	0.35**	15.65	1.30	0.062**	1.10	8.63*	2.71**	3.59	0.34	234.16**	1.42	15.93**	-1.03**	-3.36
6 RTx435	0.77*	-10.23	1.14	0.004	1.37	-0.02	1.02	0.77	0.66	120.19**	0.68	-1.65	0.55	1.22
7 SC103-12E	0.90	30.59	1.50	0.018**	2.13**	0.49	0.09	3.88	0.57	379.95**	1.79	76.67**	0.08	8.51*
8 SC599-11E	0.57**	-18.41	0.85	-0.002	1.00	1.85	0.68	0.49	0.70	36.53*	0.09	1.43	0.39	4.40
Single crosses														
1*2	1.01	92.20**	1.51	0.029**	1.64	8.21*	1.07	7.67*	0.88	117.54**	0.74	1.81	0.61	-0.68
1*3	1.21	23.70	1.02	0.001	0.56**	0.03	0.44**	-0.73	1.39	63.70**	0.80	-1.67	0.86	7.07
1*4	1.03	-18.82	0.91	-0.003	0.50*	0.46	1.75	4.94	0.94	-3.15	0.52**	-2.05	1.11	-1.11
1*6	1.14	14.85	1.29	0.015**	1.01	1.29	1.47	0.44	1.37	51.63**	0.68	-0.72	0.67**	-3.35
1*7	1.37	156.20**	1.22	0.012**	1.23	10.38*	0.91	3.66	1.70	193.56**	1.83**	-1.88	0.77	41.75**
1*8	1.13	61.33*	0.92	-0.001	1.07	0.70	1.06	-0.65	1.16	18.25	1.64	1.90	1.22	1.06
2*3	1.00	41.83*	0.92	0.003	0.91	0.19	0.94	2.99	1.05	-9.16	1.54	8.51**	1.39	-2.50
2*4	1.08	13.01	0.99	-0.002	0.87	1.63	1.46	0.36	0.94	11.61	1.14	-1.71	1.22	2.24
2*5	1.15	42.56*	1.21	0.003	0.30	2.96	1.52	1.59	0.77	-9.59	1.73	-0.18	1.32	1.52
2*6	0.90	39.26*	0.76	-0.001	1.03	0.33	1.20	0.18	1.20	29.75*	0.83	-0.84	1.71*	-0.90
2*7	1.37	56.80*	1.27	0.007*	1.36	4.09	1.28	2.97	1.16	49.06**	1.24	2.50	2.00	3.86
2*8	0.92	30.39	0.76	0.001	1.25	0.55	1.19	1.27	0.97	6.89	0.87	2.25	0.35	1.51
3*5	0.95	81.89**	0.74	0.002	0.36	13.29**	0.22	10.68**	0.98	-7.04	1.68	-1.40	0.94	-3.14
3*6	0.86	-5.71	0.73*	-0.002	0.55	8.80*	-0.05*	3.14	1.41	5.71	1.62	-1.19	1.16	9.59*
3*7	1.50**	36.80*	1.15	-0.002	1.43	1.04	-0.74*	7.40*	1.16	56.16**	0.08	-0.39	1.95	11.46**
3*8	1.33**	-14.85	1.25	-0.002	0.84	6.88	0.49	11.68**	1.13	6.47	1.44	3.66	0.65	1.95
4*6	0.85	9.63	0.74	-0.002	0.48	3.59	0.94	-0.67	0.91	49.67**	0.77	-1.52	1.67**	-3.26
4*7	1.25	9.61	0.98	-0.003	1.23	0.33	0.67	0.05	1.16	18.44	1.34	-0.80	1.78**	-1.32

Table 22. Continued.

Entry†	Grain yield		Log_{10} yield		1000-Seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
4*8	0.94	46.55*	0.78	-0.001	0.99	1.21	1.11	6.79**	0.92	40.43*	0.86	-1.96	1.19	-1.00
Three-way crosses														
(3*1)*6	0.88	25.93	0.75	0.003	0.83	-0.07	1.00	-1.03	1.15	4.94	0.65	-1.14	1.33	-0.85
(3*1)*7	1.03	28.34	0.82	-0.002	1.12	1.23	0.36*	-0.01	1.83	119.82**	1.40	1.84	1.02	-3.42
(3*1)*8	1.17	-17.88	0.98	-0.003	0.71	1.00	1.21	-0.48	1.20	5.26	0.93	-1.07	0.39	-0.17
1*(4*6)	1.20	19.88	1.09	0.002	0.88	1.58	1.48	3.70	1.13	24.78	0.81	-0.57	0.66	3.80
1*(4*7)	1.29	48.47*	1.17	0.002	1.03	0.80	0.95	1.09	0.44	141.50**	0.48	-1.77	0.41**	-2.33
1*(4*8)	1.13	-1.95	1.03	-0.002	1.07	0.22	1.04	1.25	0.94	-10.14	0.91	-1.86	0.82	-0.16
2*(3*6)	0.88	78.65**	0.82	0.009*	1.17	0.40	0.85	0.16	0.91	-0.11	1.77**	-1.85	0.69	3.25
2*(3*8)	0.91	32.75	0.85	-0.001	0.79	0.50	1.21	-0.47	0.91	-7.21	1.17	-1.59	1.11	-2.95
2*(3*7)	1.04	32.77	0.95	0.001	1.06	2.22	1.21	3.26	1.08	26.96*	0.99	-0.33	0.95	3.36
2*(4*6)	0.84	0.14	0.74*	-0.003	0.93	0.55	1.83	2.01	1.05	-5.22	1.45	-0.90	1.44**	-3.59
3*(4*7)	1.34	23.72	1.39*	0.000	1.27	2.10	0.87	11.61**	1.04	118.01**	1.37	-0.89	0.94	0.50
(2*1)*6	0.84	-8.18	0.71*	-0.002	0.61	0.55	1.30	0.39	1.07	5.87	1.09	-1.04	0.84	-3.21
(2*1)*8	1.02	114.07**	1.07	0.017**	1.16	-0.18	1.19	-0.05	0.98	11.37	1.27	-1.19	1.41**	-2.97
(3*5)*7	0.98	36.54	0.82	-0.001	1.62	2.82	0.26**	-1.12	1.11	31.50*	1.01	0.25	1.12	-3.27
(3*5)*8	0.71	80.80**	0.88	0.018	1.15	2.82	0.99	1.62	1.07	35.17*	0.51	1.24	0.91	0.03
Double crosses														
(2*1)*(3*6)	1.09	-0.21	0.95	-0.002	0.67	0.20	1.05	-0.80	1.37	29.13*	0.69	6.22	1.46**	-3.14
(2*1)*(3*7)	1.02	50.43*	1.03	0.004	0.86	0.02	0.83	0.35	1.24	42.84*	1.29	2.06	1.74	-2.26
(2*1)*(3*8)	1.04	-23.33	0.92	-0.004	1.07	-0.23	1.18	-0.07	0.90	-6.80	1.19	-0.76	0.57	-1.59
(2*1)*(4*7)	0.81	-4.07	0.67**	-0.004	1.24	0.45	1.13	-0.31	0.91	143.05**	0.41	-0.65	1.55**	-2.78
(3*1)*(4*6)	1.12	-3.58	0.95	-0.003	0.61*	-0.06	0.78	-1.26	0.75	-7.38	0.81	0.13	0.93	-3.53
(3*1)*(4*8)	1.15	20.03	1.09	0.002	0.93	1.96	0.92	3.03	0.86	-16.91	0.79	2.03	0.48*	-1.67
(3*1)*(4*7)	0.96	10.18	0.85	-0.001	0.91	2.04	0.92	1.40	0.83	23.97	0.26	0.76	0.77	-2.62
(3*2)*(4*6)	1.06	-25.49	0.98	-0.003	0.76	3.12	1.13	3.47	0.89	54.08**	0.59	1.38	1.32	-1.54
(3*2)*(4*8)	0.92	-18.79	0.95	-0.002	0.85	2.13	1.58	5.74	0.81	-6.50	1.05	-0.35	1.66**	-3.13

Table 22. Continued.

Entry†	Grain yield		Log_{10} yield		1000-Seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
(3*2)*(4*7)	0.95	21.63	0.64	0.013	0.90	0.95	1.03	-0.17	1.11	-0.70	1.11	1.99	1.40	0.45
Parents	0.71**	30.58**	1.22	0.028**	1.28	2.95**	1.10	7.98**	0.66	112.05**	0.83	12.38**	0.44	4.47**
Single crosses	1.11*	37.75**	1.01	0.003*	0.93	3.86**	0.89	3.35**	1.11	36.31**	1.12	0.23	1.19	3.41**
Three-ways	1.02	32.94**	0.94	0.002	1.03	1.09**	1.05	1.46**	1.06	33.50**	1.05	-0.73	0.94	-0.80
Double crosses	1.01	2.68	0.90	0.000	0.88	1.06**	1.06	1.14*	0.97	25.48**	0.82	1.28*	1.19	-2.18

† Parents in the crosses are identified by their respective numbers.
*, ** Significantly different from 1 for regression coefficient (b_i) and from 0 for mean square deviations (S^2_{di}) at 0.05 and 0.01 levels of probability, respectively.

Within-Plot Variability for Trials in Texas, 1991 and 1992

The ranges for plant height, panicle length, and panicle exsertion at each of the location/year combinations and combined overall environments for the 1991 and 1992 trials in Texas are shown in Appendix A, Table A2. The within-plot standard deviations for each type-group are given also. The most important characters of concern for variability in commercial production are plant height and days to maturity. Plant height uniformity is important in the U.S.A. especially due to the combine harvesting of the mature sorghum crop.

The variation in plant height at the locations and combined overall locations indicated that the differences between types were minimal in both years. However, these standard deviations were not tested statistically for their differences. Though the limits in variability that might be tolerated likely would differ among sorghum growers, the material in this study did not vary markedly. Walsh and Atkins (1973) found that mean within-plot standard deviations for plant height of three-way hybrids was significantly greater than those of single crosses, but the differences did not seem large enough to be important agronomically. Similar sentiments could be made of the variability in the present study. Stephen and Lahr (1959) had earlier concluded that single cross and three-way cross hybrids need not differ markedly in plant-to-plant variation for height. Rosenow (1968) had suggested that care be taken in the selection of parents for three-way cross hybrids if variability is to be minimized.

Heterosis (High-Parent) for Grain Yield in Texas Trials

High-parent heterosis were calculated for single cross and three-way cross hybrids. The levels of heterosis on an individual location/year basis in Texas are presented in Appendix B, Table B1. The percentage data for the individual hybrids ranged from -44.8 to 207.9%. The amount of heterosis observed depended on the location, year and type of cross; i.e. single or three-way. The single crosses indicated higher heterosis than did the three-way crosses. Negative heterosis values were preponderant in the three-way crosses that involved a male-sterile (A-) line as the female and a male-fertile F_1 as the male parent. This is expected due to the fact that the three-way hybrid will in this case be compared with the fertile single cross hybrid for high-parent heterosis. However none of the negative heterotic values were significant. From these results it appears that the most appropriate three-way cross for commercial hybrid production would have a male-sterile F_1 and a fertility-restoring line as the parents. The three-way crosses involving A_2Tx632*RTx430 as the sterile F_1 female parent also indicated negative heterosis. This sterile F_1 was high yielding at all the environments tested and involves an A_2 cytoplasm female with an A_1 cytoplasm restorer male parent. RTx430 restores fertility in A_1 cytoplasm but acts as a maintainer in the A_2 cytoplasm.

Crosses involving SC103-12E indicated high heterotic values in the single crosses. Among the three-way crosses only (ATx631*ATx630)*SC599-11E indicated consistency in the significance of heterosis across the environments. Examination of the actual means of the parents and their hybrids for grain yield reveals a tendency for a relatively high percentage heterosis to be expressed by hybrids whose parents were comparatively low yielding. Percentage heterosis, therefore, appeared associated with differences in the "base' performance of the parental varieties *per se* rather than with differences in the amount of heterosis expressed by the different crosses. Similar observations were reported by Kirby and Atkins (1968) who also observed several instances of high percentage heterosis when the most diverse parents were crossed. Niehaus and Pickett (1966) had also observed that heterosis was most striking when one of the parents was an introduction.

Prediction of Three-way Cross Grain Yield in Texas Trials

The three-way crosses mean grain yields were predicted using the model adapted from Jenkins' (1934) Method B. In this model the grain yield of the three-way cross is predicted by averaging the means of the two non-parental single-crosses. The predicted values and the simple correlation coefficients between the observed and predicted mean yields for the three-way crosses at each environment and combined overall the environments are in Appendix D, Table D1. Highly significant correlations were indicated between the observed and predicted means at Corpus Christi in 1991 (0.71**) and at Chillicothe (0.72**). These results when compared with the extensive information drawn from similar studies in maize, point to the use of the non-parental single crosses as appropriate in the prediction of grain yield in sorghum three-way hybrids.

Trials in Kenya during 1992/93

Performances at Individual Locations in Kenya

The results for the experiments in Kenya at individual locations are presented in Tables 23 to 30. The estimated mean squares for each of the characters studied at Kibos during the long rainy season of 1992 are shown in Table 23. Highly significant ($P \leq 0.01$) differences were indicated among the entries for all the characters. Partitioning of the variability due to entries into among type-groups indicated highly significant differences among the parental lines and among the fertile single crosses for all the characters except 1000-seed weight. Among sterile single

Table 23. Estimated mean squares for agronomic characters in sorghum at Kibos in 1992.

Source	df	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}	%	g	d	cm	cm	cm
Replications	2	249.35*†	35.43	60.17**	3.69	41.82	8.85	105.14**
Entries	53	960.05**	80.19**	21.29**	54.04**	5070.04**	27.11**	87.15**
Among Parents	7	597.61**	118.54**	39.91	72.95**	692.27**	37.19**	133.95**
Among SSC	5	1782.04**	291.78**	32.49	23.56	530.70**	35.11**	44.96**
Among FSC	15	837.69**	88.26**	16.93	69.21**	5701.84**	37.01**	44.29**
Among TWC	23	530.75**	25.40	10.83	13.68	4334.29**	10.21**	63.91**
Types	3	6714.88**	406.82**	61.21**	294.21**	25332.12**	70.36**	440.67**
Parents vs Hybrids	1	11490.05**	309.74**	165.81**	235.13**	59553.62**	178.88**	742.77**
SSC vs (FSC+TWC)	1	4462.29**	905.29**	16.89	614.13**	15666.48**	21.29**	578.98**
FSC vs TWC	1	4192.28**	5.43	0.94	33.37	776.26**	10.90	0.27
Error	106	68.55	25.48	4.85	12.07	90.05	3.09	13.06
Location means		3767.39	76.25	25.93	66.61	171.79	30.57	10.92
CV %		21.98	6.62	8.50	5.22	5.52	5.75	33.10
LSD (0.05)		1340.20	8.17	3.57	5.62	15.36	2.84	5.85

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.
† Multiply mean squares in the column by 10^4.
SSC, FSC, and TWC : Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

crosses, the variability was highly significant for all the characters except 1000-seed weight and days to 50% anthesis. Variability among three-way crosses was highly significant for grain yield, plant height, panicle length, and panicle exsertion. The different type-groups differed significantly for all the characters, as indicated by the mean squares for types (Table 23).

The sums of squares for among type-groups was partitioned into useful single-degree-of-freedom contrasts for comparison among the types. The comparison of parental lines vs hybrids was highly significant for all the characters. The sterile single crosses vs fertile single and three-way crosses indicated highly significant differences for all the characters except 1000-seed weight. Fertile single crosses vs three-way hybrids was significant for grain yield and plant height. The separation of the single cross hybrids into components of sterile and fertile was deemed necessary in order to compare the sterile F_1's to the B-lines (in lieu of A-lines) in terms of hybrid seed production. Hookstra and Rose (1982) recommended that use of sterile F_1 female parents in hybrids can reduce production costs to the seed producers and seed costs to the farmer if acceptable, high performing three-way sorghum hybrids are identified. On the other hand, the most useful comparison for the producers is the performance of three-way hybrids as they compare to that of single cross hybrids.

The means of performance for each entry and type-group, for the agronomic characters studied are shown in Table 24. Mean grain yields for all the entries ranged from 280 kg/ha, in the parental line BTx635 to 7119 kg/ha in the three-way cross (ATx3197*BTx631)*Serena, with an overall entries mean of 3767 kg/ha. The coefficient of variation (CV) for grain yield at Kibos was 22%. Five cultivars did not differ significantly from the highest yielding cultivar; these included three three-way hybrids and two fertile single crosses. Serena, a widely cultivated local variety, was the male parent in three of the four high yielding three-way crosses, and in both the high yielding single crosses.

Threshing percentage ranged from 62%, in a parental line BTx630 to 87% in the fertile single cross ATx635*SC599-11E, with a location mean of 76% and a CV of 6.6%. 1000-seed weight had a range among the entries of 19.3 g in the parental line BTx635, to 31.7 g in another parental line RTx432, a location mean at 25.9 g and a CV of 8.5%. Days to 50% anthesis ranged from 58 d, in a fertile single cross ATx3197*Serena to 76 d in ATx3197*Lulu D. The mean days to 50% anthesis at Kibos were 67 d with a CV of 5.2%. The range in plant height was 106 cm, in parental lines SC599-11E and RTx432 to 268 cm in the fertile single cross ATx635*BTx631, with a mean of 172 cm and 5.5% CV. Panicle length ranged from 23.4 cm in BTx3197 to 36.6 cm in the sterile single cross ATx635*BTx631 with a mean of 30.6 cm and 5.8% CV. The panicle exsertion ranged from -4.0 cm in Lulu D to 21.5 cm in the fertile single cross ATx3197*SC599-11E.

Comparisons among the type-groups using the LSD (P=0.05) test indicated that the

Table 24. Means for agronomic characters in sorghum parents, single and three-way-cross hybrids at Kibos in 1992.

Entry†	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Parents							
1 BTx630	582	62	22.3	73	138	29.7	8.2
2 BTx631	1077	66	22.7	75	138	33.3	3.7
3 BTx3197	1597	76	23.7	66	119	23.4	8.1
4 BTx635	280	73	19.3	73	128	25.1	7.7
5 Serena	4543	77	24.7	71	148	26.0	-2.7
6 Lulu D	3100	71	21.7	72	124	27.1	-4.0
7 RTx432	1208	82	31.7	65	106	27.2	8.6
8 SC599-11E	1597	76	22.0	61	106	32.6	16.6
Mean	1748 c‡	73 b	23.5b	70 a	126b	28.1b	5.8b
Sterile Single Crosses							
2*1	1320	70	27.7	74	146	35.0	3.1
3*1	2686	69	29.0	71	149	28.1	7.5
3*2	4176	78	26.3	67	142	28.9	11.5
4*3	3356	72	26.0	72	144	30.5	7.0
4*1	2857	69	24.0	71	178	33.1	9.0
4*2	1509	64	19.7	75	154	36.6	1.0
Mean	2650 c	70 b	25.4a	72 a	152b	32.0a	6.5b
Fertile Single Crosses							
1*5	4319	77	29.3	68	245	31.7	10.2
1*6	4923	82	27.3	68	183	31.8	8.3
1*7	3900	82	26.0	63	150	33.3	10.0
1*8	3366	78	26.3	62	150	36.3	13.6
2*5	5691	77	27.3	65	268	31.1	8.5
2*6	4040	69	26.0	67	184	34.5	9.6
2*7	3168	72	25.7	65	153	31.7	8.4
2*8	1259	75	23.3	72	146	36.2	13.2
3*5	5894	78	31.0	58	252	28.8	16.0
3*6	767	67	22.3	76	156	25.5	14.9
3*7	2120	76	27.3	59	151	27.6	18.1
3*8	3706	82	23.7	61	143	29.1	21.5
4*5	5956	79	28.7	64	238	28.4	10.9
4*6	821	75	24.0	72	151	25.6	10.0
4*7	3620	86	28.7	70	162	32.2	14.0
4*8	4290	87	25.0	66	162	36.0	15.3
Mean	3615 b	76 a	26.4a	66 b	181a	31.2a	12.7a

Table 24. Continued.

Entry	Grain yield	Threshing percent	1000-seeds weight	days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Three-Way Crosses							
(2*1)*5	4873	74	28.7	65	256	30.1	7.3
(2*1)*6	1703	73	26.3	69	168	30.4	10.4
(2*1)*7	4672	77	26.3	66	155	31.7	10.1
(2*1)*8	2093	72	26.0	69	165	33.2	8.6
(3*1)*5	6219	75	29.3	64	243	29.4	10.9
(3*1)*6	5583	77	25.3	65	166	29.3	9.7
(3*1)*7	3319	83	29.3	62	169	27.7	17.6
(3*1)*8	4400	80	22.3	61	148	32.0	19.7
(4*1)*5	6686	79	29.7	66	254	29.5	6.3
(4*1)*6	6369	79	25.7	67	172	29.1	10.9
(4*1)*7	3708	76	25.7	64	163	31.2	13.2
(4*1)*8	5301	79	28.0	64	170	34.6	17.6
(3*2)*5	7119	79	29.3	63	253	28.9	11.4
(3*2)*6	5430	76	25.3	66	174	30.0	11.5
(3*2)*7	5046	78	24.7	63	159	29.4	15.1
(3*2)*8	3080	79	24.0	63	145	30.4	20.1
(4*2)*5	4480	79	28.3	65	239	29.3	7.6
(4*2)*6	4762	77	25.3	67	163	32.3	6.7
(4*2)*7	4904	80	25.3	68	183	32.7	10.9
(4*2)*8	4108	82	25.0	65	162	33.3	17.6
(4*3)*5	5732	78	27.7	65	245	29.3	7.7
(4*3)*6	5590	77	26.3	64	160	27.7	11.8
(4*3)*7	5220	78	26.0	63	189	30.3	17.7
(4*3)*8	5317	84	27.3	63	165	33.1	21.4
Means	4821 a	78 a	26.6a	65 b	186a	30.6a	12.6a
General mean	3767	76	25.9	67	172	30.6	10.9
LSD(0.05)	1340	8.2	3.6	5.6	15.4	2.8	5.9

† In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx631 single cross and Serena.
‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

parental (B- and R-) lines were not significantly different from the sterile single crosses, in their means for grain yield, threshing percentage, days to 50% anthesis, plant height and panicle length. However, the sterile single crosses indicated a higher grain yield (2650 kg/ha) than the parental lines (1748 kg/ha). Even though the differences are not significant, the 900 kg/ha (51%) obtained in the sterile single crosses over the B-lines and R-lines is appreciable. Also the B-lines, though considered isolines to the respective A-lines, are fertile and therefore a bias is introduced in this comparison. The sterile single crosses indicated higher 1000-seed weight, which might have contributed to the higher grain yield in the sterile F_1. Walsh and Atkins (1973) attributed the superiority of the sterile F_1's to the greater number of seeds/panicle. Hookstra and Ross (1982) attributed the yield increase to more seeds/panicle, panicles/plant, and a greater threshing percent.

The three-way crosses indicated a significantly higher mean grain yields over the fertile single crosses at Kibos, with a difference of 1200 kg/ha (33 %).The means for components of yield (threshing percentage and 1000-seed weight), days to 50% anthesis, plant height, panicle length, and panicle exsertion were nearly alike for three-way and single cross hybrids, indicating nonsignificant differences according to the LSD test.

A summary of the analysis of variance mean squares for the agronomic characters studied at Kiboko is presented in Table 25. Two characters, 1000-seed weight and days to 50% anthesis, were not recorded at Kiboko. Highly significant differences were indicated for the variability among all the entries for all the characters. The sums of squares for entries were partitioned to assess the variability exhibited among the entries within type-groups. The variability among parental lines was highly significant for all the traits except plant height (Table 25). Among the sterile single crosses, only grain yield indicated significant differences. The differences among fertile single crosses were significant for all characters except threshing percentage. Among three-way cross hybrids significant differences were indicated for grain yield and panicle length. Highly significant differences were indicated among the different type-groups.

Partitioning of the sums of squares for types into single-degree-of-freedom contrasts (Table 25) indicated that parental lines vs hybrids differences were highly significant for all the traits studied. Sterile single crosses vs fertile single and three-way crosses was highly significant ($P \leq 0.01$) for all characters except panicle length. The contrast fertile single crosses vs three-way crosses indicated significant differences for grain yield and panicle exsertion.

The means for agronomic characters at Kiboko are shown in Table 26. The mean grain yields of the entries ranged from 444 kg/ha in three of the parental lines, BTx630, RTx432 and SC599-12E to 5889 kg/ha in the single cross ATx635*Serena, and in the three-way cross hybrid (ATx3197*BTx630)*RTx432. Only one other cultivar, the three-way cross (ATx635*BTx631)*Serena (5000 kg/ha) did not differ significantly from the highest yielding cultivars. The mean grain yields

Table 25. Estimated mean squares for agronomic characters in sorghum at Kiboko in 1992.

Source	df	Grain yield	Threshing percent	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}	%	cm	cm	cm
Replications	2	334.59**†	310.96**	180.66	1.41	73.46**
Entries	53	469.26**	172.40**	1244.74**	24.69**	64.11**
Among Parents	7	399.93**	466.18**	470.86	19.33**	98.43**
Among SSC	5	311.76**	123.37	127.39	5.93	17.57
Among FSC	15	370.27**	57.37	871.88*	17.46**	26.04*
Among TWC	23	204.59**	53.47	465.41	19.98**	10.98
Types	3	3417.57**	1055.69**	12752.05**	140.69**	659.24**
Parents vs Hybrids	1	6767.88**	2068.54**	33842.33**	404.62**	1249.21**
SSC vs (FSC+TWC)	1	3092.22**	1066.85**	3394.98**	16.99	661.61**
FSC vs TWC	1	392.60**	31.67	1018.83	0.46	66.89*
Error	106	48.81	59.62	432.11	6.21	12.95
Location means		2813.79	72.28	141.30	28.14	14.84
CV %		24.83	10.68	5.52	8.85	24.25
LSD (0.05)		1130.90	12.50	14.71	4.03	5.83

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

† Multiply mean squares in the column by 10^4.

SSC, FSC, and TWC : Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

Table 26. Means for agronomic characters in sorghum parents, single and three-way-cross hybrids at Kiboko in 1992.

Entry†	Grain yield	Threshing percent	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	cm	cm	cm
Parents					
1 BTx630	444	50	112	26.2	8.5
2 BTx631	777	69	87	21.7	0.0
3 BTx3197	1111	67	120	24.4	11.6
4 BTx635	889	67	108	25.4	3.1
5 Serena	3667	79	125	20.5	9.5
6 Lulu D	2333	77	97	23.8	4.0
7 RTx432	444	44	104	24.2	10.7
8 SC599-11E	444	56	101	28.7	18.1
Mean	1264 b‡	64 b	107 b	24.4b	8.2b
Sterile Single Crosses					
2*1	556	56	127	29.0	6.6
3*1	1167	65	134	27.8	9.9
3*2	2444	67	129	29.4	14.0
4*3	3333	75	134	29.3	11.1
4*1	1333	67	139	31.8	9.7
4*2	2333	71	144	30.9	10.8
Mean	1861 b	67 b	135 b	29.7a	10.3b
Fertile Single Crosses					
1*5	2000	76	167	29.9	16.5
1*6	3111	75	145	27.5	15.2
1*7	2444	68	143	29.0	15.7
1*8	3222	75	168	29.9	16.3
2*5	2778	79	179	28.7	14.4
2*6	3722	76	154	31.9	10.3
2*7	3667	73	148	32.1	12.5
2*8	3444	80	171	32.6	12.3
3*5	4111	78	172	26.3	20.3
3*6	1889	71	134	27.1	16.3
3*7	2667	73	136	26.7	17.7
3*8	1667	72	126	26.8	18.0
4*5	5889	77	175	26.4	21.5
4*6	3889	79	135	24.8	13.1
4*7	1444	63	139	28.6	17.2
4*8	2778	74	155	31.8	17.7
Mean	3045 a	74 a	153 a	28.8a	15.9a

Table 26. Continued.

Entry	Grain yield	Threshing percent	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	cm	cm	cm
Three-Way Crosses					
(2*1)*5	2889	70	164	27.0	17.2
(2*1)*6	3667	74	163	29.6	19.2
(2*1)*7	2222	80	143	28.5	17.1
(2*1)*8	3000	73	133	31.6	19.2
(3*1)*5	3222	71	130	26.7	15.4
(3*1)*6	3111	74	134	24.8	17.3
(3*1)*7	5889	82	138	28.1	18.9
(3*1)*8	3333	81	133	30.9	17.5
(4*1)*5	2778	75	149	23.9	15.1
(4*1)*6	3333	77	137	27.0	16.4
(4*1)*7	4000	73	146	27.6	14.6
(4*1)*8	2889	73	153	28.1	22.2
(3*2)*5	3333	69	165	29.2	18.6
(3*2)*6	3000	73	151	29.2	17.3
(3*2)*7	3889	78	151	25.5	18.8
(3*2)*8	3556	85	137	30.9	21.3
(4*2)*5	5000	77	182	26.1	17.8
(4*2)*6	3889	67	141	28.1	16.6
(4*2)*7	2556	73	151	31.0	18.5
(4*2)*8	4222	79	153	34.4	16.4
(4*3)*5	3222	77	151	26.8	16.7
(4*3)*6	2722	78	136	28.3	15.4
(4*3)*7	2333	72	139	30.4	14.7
(4*3)*8	3889	77	145	33.4	16.9
Means	3414 a	75 a	147 a	28.6a	17.5a
General mean	2814	72	141	28.1	14.8
LSD(0.05)	1130.9	12.5	33.7	4.0	5.8

† In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx630 single cross and Serena.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

among the types were 1264 kg/ha for parental lines, 1861 kg/ha among sterile single crosses, 3045 kg/ha for fertile single crosses, and 3414 kg/ha in the three-way hybrids. The difference between the parental lines and the sterile single crosses in mean grain yield was not significant (LSD test). The sterile single crosses indicated a 47% yielding superiority over the fertile parental lines at Kiboko. Similarly, the difference in mean grain yield for fertile single crosses and three-way crosses was not significant according to the LSD test (Table 26) though the orthogonal contrast fertile single crosses vs three-way crosses had indicated highly significant differences (Table 25). The three-way crosses outyielded the fertile single crosses by an average of 12% at Kiboko.

The differences in the other agronomic characters, threshing percentage, plant height, panicle length, and panicle exsertion, between parental lines and sterile single crosses were not significant except for panicle length.The sterile single cross had longer panicles than the parental lines. Plant height in the sterile single crosses, though not significantly greater than in the parental lines, was on average 28 cm more. The differences in these characters between fertile single crosses and three-way crosses were not significantly different (LSD test), and were nearly alike for the characters.

The estimated mean squares for the characters studied at Kakamega during the long rainy season of 1991 are presented in Table 27. Highly significant ($P \leq 0.01$) differences were indicated among the entries for all the traits. Variability among the parental lines, among fertile single crosses, and among the three-way hybrids were also significant for all the traits. Among the sterile single crosses, nonsignificant differences were indicated for 1000-seed weight. The variability among type-groups were significant for all the traits except threshing percentage. The three hybrid-types and the parental lines (parents vs hybrids) were significantly different for all characters except threshing percentage. Sterile single crosses vs parental lines was not significant for 1000-seed weight and panicle length. Fertile single crosses vs three-way crosses indicated nonsignificant differences for all the traits except days to 50% anthesis (Table 27).

The means for all the agronomic characters for the entries at Kakamega, during the long rainy season, in 1991 are shown in Table 28. The mean grain yields ranged from 737 kg/ha in the sterile single cross ATx635*BTx630 to 5709 kg/ha in the fertile single cross, ATx3197*Serena. Only one entry, a three-way cross, (ATx635*RTx430)*Serena, did not differ significantly in grain yield from the best yielding entry. The mean yield at the location was 2236 kg/ha, with a CV of 16.4%. The means for each of the type-groups were, 1956 kg/ha for parental lines, 1800 kg/ha for sterile single crosses, 2383 kg/ha in the fertile single crosses, and 2341 kg/ha in the three-way crosses. These means did not differ significantly according to the LSD test (Table 28).

The three-way crosses and the fertile single crosses did not differ significantly for any of the traits according to the LSD test. However, the orthogonal contrasts in the analysis of variance

Table 27. Estimated mean squares for agronomic characters in sorghum at Kakamega during the long rainy season in 1992.

Source	df	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}	%	g	d	cm	cm	cm
Replications	2	22.45†	71.69	8.67	13.72**	1409.68*	45.62**	33.47*
Entries	53	460.09**	307.00**	34.91**	23.93**	3091.44**	25.05**	89.11**
Among Parents	7	274.29**	356.79**	43.90**	55.52**	793.28**	28.67**	119.66**
Among SSC	5	148.00**	209.35**	28.06	15.66**	832.58**	19.53*	67.89**
Among FSC	15	642.88**	385.10**	28.24*	11.84**	3589.83**	17.97**	125.72**
Among TWC	23	494.22**	290.67**	35.73**	6.94**	2504.77**	19.01**	40.61**
Types	3	238.22**	88.18	52.45*	154.76**	14224.34**	107.56**	241.89**
Parents vs Hybrids	1	221.68**	11.24	128.33**	300.14**	35200.61**	293.08**	333.29**
SSC vs (FSC+TWC)	1	487.90**	233.51*	11.91	148.54**	7368.00**	8.38	358.29**
FSC vs TWC	1	5.07	19.79	17.11	15.61*	104.43	21.22	33.54
Error	106	13.48	42.23	14.96	2.50	121.74	6.66	9.27
Location means		2236.34	64.31	26.93	75.28	154.66	27.88	8.25
CV %		16.42	10.11	14.36	2.10	7.13	9.26	36.91
LSD (0.05)		594.40	10.52	6.26	2.56	17.86	4.18	4.93

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

† Multiply mean squares in the column by 10^4.

SSC, FSC, and TWC : Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

Table 28. Means for agronomic characters in sorghum parents, single, and three-way-cross hybrids at Kakamega during the long rainy season in 1992.

Entry†	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Parents							
1 BTx630	859	47	26.7	83	132	26.7	1.5
2 BTx631	934	52	21.7	85	124	27.9	1.1
3 BTx3197	2731	66	28.3	78	120	20.8	10.5
4 BTx635	2323	74	23.3	80	127	23.2	10.6
5 Serena	3649	81	30.0	73	146	20.7	1.9
6 Lulu D	2197	67	18.3	78	105	25.0	-5.4
7 RTx432	1607	61	16.7	73	98	23.9	4.6
8 SC599-11E	1347	61	23.3	78	104	28.9	13.5
Mean	1956 a‡	64 a	24.8b	79 a	119b	24.7b	4.8b
Sterile Single Crosses							
2*1	1511	66	31.7	79	127	29.3	-1.8
3*1	2552	73	30.0	77	142	24.6	8.6
3*2	1766	62	26.7	77	121	28.2	-0.3
4*3	2609	58	30.0	76	144	26.9	6.9
4*1	737	49	23.3	81	166	31.8	4.9
4*2	1623	61	26.7	74	152	26.0	9.8
Mean	1800 a	61 a	28.1ab	77 a	142b	27.8a	4.7b
Fertile Single Crosses							
1*5	2944	75	25.7	72	226	26.9	9.3
1*6	842	51	28.3	75	165	29.3	10.3
1*7	3283	74	28.3	74	143	29.7	2.1
1*8	2372	69	23.3	75	145	30.5	9.7
2*5	5034	80	31.7	73	228	28.0	1.6
2*6	789	38	26.7	76	158	25.2	9.7
2*7	836	54	21.7	79	129	30.7	-0.9
2*8	953	55	23.3	78	133	30.8	2.7
3*5	5709	79	31.7	71	220	25.2	12.5
3*6	2287	60	26.7	74	155	23.6	21.6
3*7	2206	66	30.0	74	150	26.4	16.0
3*8	1727	64	28.3	75	138	26.8	20.3
4*5	3789	77	30.0	73	207	25.9	10.4
4*6	1929	60	26.7	75	144	27.7	9.3
4*7	1829	68	31.7	75	141	29.4	11.3
4*8	1601	63	28.3	76	155	32.1	16.1
Mean	2383 a	64 a	27.7a	75 b	165a	28.0a	10.1a

Table 28. Continued.

Entry	Grain yield	Threshing percent	1000-seeds weight	days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Three-Way Crosses							
(2*1)*5	3497	79	28.3	72	208	26.3	3.7
(2*1)*6	2217	65	30.0	76	143	26.5	5.2
(2*1)*7	1897	63	26.7	74	138	30.4	1.5
(2*1)*8	2290	67	25.0	75	133	33.1	2.8
(3*1)*5	4463	78	31.7	72	180	29.6	11.9
(3*1)*6	1737	56	30.0	73	167	29.3	12.3
(3*1)*7	1051	49	31.7	73	140	27.2	9.8
(3*1)*8	1617	66	21.7	75	135	30.0	12.5
(4*1)*5	5294	75	31.7	72	205	25.3	12.6
(4*1)*6	1101	51	21.7	75	160	29.2	7.2
(4*1)*7	1077	58	26.7	75	156	29.2	9.3
(4*1)*8	1162	59	23.3	76	233	28.4	9.6
(3*2)*5	3366	77	28.3	72	158	32.6	13.0
(3*2)*6	1546	55	28.3	75	166	29.3	11.1
(3*2)*7	3446	77	26.7	74	146	29.2	6.6
(3*2)*8	1444	58	30.0	75	138	30.7	10.6
(4*2)*5	4402	75	30.0	72	225	26.5	7.4
(4*2)*6	1006	51	23.3	76	157	28.8	6.4
(4*2)*7	1372	58	26.7	76	146	28.1	6.3
(4*2)*8	2247	71	20.0	75	148	32.1	12.6
(4*3)*5	4354	80	28.3	72	190	22.0	14.5
(4*3)*6	1529	65	21.7	73	145	28.3	7.9
(4*3)*7	1563	60	26.7	73	145	28.4	7.3
(4*3)*8	2511	73	26.7	75	149	32.4	14.8
Means	2341 a	65 a	26.9ab	74 b	186a	30.6a	12.6a
General mean	2236	64	26.9	75	155	27.9	8.3
LSD(0.05)	594.4	10.5	6.3	2.6	17.9	4.2	4.9

† In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx631 single cross and Serena.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

(Table 27) had indicated significant differences for fertile single crosses vs three-way crosses for plant height. Three-way crosses were 20 cm taller, on the average, than the fertile single crosses.

Table 29 gives a summary of the estimated mean squares for all the characters studied at Kakamega during the short rainy season, 1992/93. The variability among the entries indicated highly significant differences ($P \leq 0.01$) for all the traits except 1000-seed weight. The mean squares for 1000-seed weight had a probability level of 0.06, which is close to 0.05, and for the purpose of interpretation in this study, will be considered significant. The differences among parental lines were similarly found to be significant for all the traits except 1000-seed weight. Among sterile single crosses and among fertile single crosses, significant differences were indicated for grain yield, days to 50% anthesis and plant height. Significant differences were indicated among three-way crosses for grain yield, plant height and panicle length. The differences among the different type-groups were highly significant for all the characters. The comparison parents vs hybrids was significant for all the attributes. Sterile single crosses vs fertile single crosses and three-way crosses was not significant for 1000-seed weight and panicle length, whereas the comparison of fertile single crosses vs three-way crosses was significant for grain yield and threshing percentage.

The entry means at Kakamega during the short rainy season are presented in Table 30. Mean yields for all the entries ranged from 359 kg/ha in the parental line RTx432 to 9426 kg/ha in a fertile single cross ATx635*RTx432. A three-way cross (ATx3197*BTx630)*RTx432 was second ranking (8206 kg/ha) but was significantly different from the best yielding cultivar. The overall entries mean grain yield was 3795 kg/ha, with a CV of 19.3%. The respective means for each type-group were 1816 kg/ha in the parental lines, 3446 kg/ha for the sterile single crosses, 4059 kg/ha for fertile single crosses, and 4366 kg/ha for three-way crosses. The sterile single crosses significantly outyielded the parental lines, while the difference between the three-way crosses and fertile single crosses was not significant according to the LSD test (Table 30). However, the three-way crosses outyielded the fertile single crosses by about 8% at Kakamega during the short rainy season. The sterile single crosses significantly outperformed the parental lines in most of the other traits except threshing percentage, in which the parental lines indicated a higher mean percentage. The fertile single crosses and three-way hybrids differed significantly (LSD test) in threshing percentage, with the other traits being similar for the two types of hybrids.

At Alupe, in 1992, data were collected for plant height, panicle length, and panicle exsertion. The three characters were significantly different among the entries (Table 31). Differences among parents, among fertile single crosses, and among three-way crosses were significant for all the characters. Among sterile single crosses, significant differences were indicated for plant height and panicle exsertion. The differences among type-groups were significant for the

Table 29. Estimated mean squares for agronomic characters in sorghum at Kakamega during the short rainy season in 1992.

Source	df	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}	%	g	d	cm	cm	cm
Replications	2	184.40*†	21.01	5.39	51.19**	261.69*	28.53**	6.79
Entries	53	1491.80**	62.18**	17.40	26.00**	1702.80**	13.25**	52.37**
Among Parents	7	665.88**	96.31**	19.33	44.55**	495.58**	25.46**	55.18**
Among SSC	5	640.92**	24.68	2.09	15.33*	1800.82**	8.36	25.78
Among FSC	15	2348.50**	18.00	4.69	11.71**	1225.54**	8.71	21.92
Among TWC	23	1029.28**	21.50	13.72	4.29	1318.74**	8.22*	12.50
Types	3	4099.62**	577.93**	130.17**	238.47**	9687.02**	54.20**	548.04**
Parents vs Hybrids	1	11033.10**	291.00**	352.47**	405.39**	27033.10**	148.44**	1433.37**
SSC vs (FSC+TWC)	1	995.30**	1362.86**	22.44	309.95**	1890.85**	7.38	210.63**
FSC vs TWC	1	270.45*	79.94**	15.61	0.09	137.11	6.77	0.12
Error	106	53.59	14.36	12.16	5.47	57.33	5.00	13.45
Location means		3794.80	73.67	25.87	77.46	154.23	25.54	16.58
CV %		19.29	5.14	13.48	3.02	4.91	8.76	22.12
LSD (0.05)		1185.00	6.13	5.65	3.79	12.26	3.62	5.94

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.

† Multiply mean squares in the column by 10^4.

SSC, FSC, and TWC : Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

Table 30. Means for agronomic characters in sorghum parents, single and three-way-cross hybrids at Kakamega during the short rainy season in 1992/93.

Entry†	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Parents							
1 BTx630	1473	62	25.0	82	146	24.1	11.2
2 BTx631	529	66	21.7	86	128	25.1	10.7
3 BTx3197	1668	74	23.7	84	124	20.5	12.5
4 BTx635	1066	73	20.3	84	119	21.6	12.0
5 Serena	5025	79	25.7	75	136	18.6	3.5
6 Lulu D	2681	75	20.0	83	111	23.0	1.9
7 RTx432	359	69	18.7	77	110	25.4	10.7
8 SC599-11E	1725	67	23.7	79	114	27.6	13.1
Mean	1816 b‡	71 c	22.3b	81 a	123c	23.2b	9.5b
Sterile Single Crosses							
2*1	1464	61	25.3	83	128	28.5	11.1
3*1	4351	67	25.0	78	147	27.0	15.4
3*2	1979	67	25.0	79	129	24.7	11.1
4*3	5318	68	25.7	78	142	26.1	15.9
4*1	3622	65	27.0	82	163	28.2	15.9
4*2	3939	68	24.7	83	192	24.7	18.4
Mean	3446 a	66 d	25.4b	81 a	150b	26.5a	14.6b
Fertile Single Crosses							
1*5	3839	71	27.3	75	193	25.5	15.6
1*6	4244	75	24.7	76	159	26.9	19.2
1*7	811	73	29.0	76	146	24.8	17.9
1*8	4600	76	26.3	78	146	27.8	20.5
2*5	8158	77	27.0	75	197	26.6	11.9
2*6	2757	72	25.3	80	161	28.7	18.7
2*7	2437	74	28.0	78	145	25.7	16.3
2*8	2170	74	28.3	78	140	29.3	16.5
3*5	6352	78	26.7	73	192	23.6	17.0
3*6	768	70	29.3	79	145	25.4	17.5
3*7	6649	74	27.0	73	147	24.9	20.1
3*8	592	73	27.0	77	143	24.5	19.3
4*5	9426	78	26.3	75	187	24.7	19.1
4*6	6655	77	27.0	75	145	24.8	17.4
4*7	4742	76	28.0	76	154	26.3	21.5
4*8	746	73	26.0	76	156	28.5	23.7
Mean	4059 a	75 b	27.1a	76 b	160ab	26.1a	18.3b

Table 30. Continued.

Entry	Grain yield	Threshing percent	1000-seeds weight	days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Three-Way Crosses							
(2*1)*5	3755	74	24.3	76	205	26.4	15.6
(2*1)*6	2082	74	23.0	79	157	26.6	16.7
(2*1)*7	1745	73	31.3	77	153	26.6	15.3
(2*1)*8	5274	73	26.0	77	148	28.1	19.3
(3*1)*5	3734	76	29.3	75	195	25.7	15.7
(3*1)*6	7148	75	24.7	75	160	24.7	19.4
(3*1)*7	8206	78	27.3	76	153	23.5	16.2
(3*1)*8	3441	75	29.0	76	145	26.2	20.2
(4*1)*5	4919	78	26.0	75	196	24.3	17.1
(4*1)*6	4141	78	26.0	76	150	26.0	14.9
(4*1)*7	3881	72	27.3	76	156	25.5	19.9
(4*1)*8	2099	76	26.7	75	160	27.3	22.5
(3*2)*5	3338	74	26.7	77	195	23.7	20.6
(3*2)*6	7451	75	28.7	76	155	23.6	20.4
(3*2)*7	4460	77	26.7	75	140	23.3	16.7
(3*2)*8	2975	80	26.0	76	134	25.6	19.0
(4*2)*5	5213	78	21.0	74	192	23.3	17.3
(4*2)*6	7272	72	27.0	76	150	25.9	17.5
(4*2)*7	2236	75	27.7	77	152	26.1	19.8
(4*2)*8	6103	81	26.0	77	159	29.2	19.1
(4*3)*5	3984	79	25.3	76	191	23.6	18.8
(4*3)*6	5449	79	25.0	76	146	26.1	17.5
(4*3)*7	2068	74	27.0	76	147	25.7	20.4
(4*3)*8	3800	80	24.3	78	149	28.2	20.1
Means	4366 a	76 a	26.4a	76 b	162a	25.7a	18.3a
General mean	3795	79	25.9	78	154	25.5	16.6
LSD(0.05)	1185.0	6.1	5.7	3.8	12.3	3.6	5.9

† In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx631 single cross and Serena.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

Table 31. Estimated mean squares for plant height, panicle length and panicle exsertion in sorghum at Alupe in 1992.

Source	df	Plant height	Panicle length	Panicle exsertion
		cm	cm	cm
Replications	2	1190.92**	46.84**	136.56**
Entries	53	2071.13**	22.61**	79.41**
Among Parents	7	519.52**	18.72**	176.89**
Among SSC	5	1919.51**	10.55	33.23*
Among FSC	15	1843.40**	21.76**	36.35**
Among TWC	23	1324.29**	10.29*	29.69**
Types	3	12808.77**	150.46**	525.45*
Parents vs Hybrids	1	221.68**	11.24	525.34**
SSC vs (FSC+TWC)	1	2548.01**	5.13	352.78**
FSC vs TWC	1	132.78	36.90**	36.18
Error	106	106.56	5.18	11.34
Location means		149.81	27.03	17.87
CV %		6.89	8.42	18.85
LSD (0.05)		16.71	3.68	5.45

*, ** Significant at 0.05 and 0.01 levels of probability, respectively.
SSC, FSC, and TWC : Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

Table 32. Means for plant height, panicle length and exsertion in sorghum parents, single, and three-way cross hybrids at Alupe in 1992.

Entry†		Plant height	Panicle length	Panicle exsertion
Parents		cm	cm	cm
1	BTx630	130	23.2	13.5
2	BTx631	121	27.1	15.7
3	BTx3197	115	20.7	15.6
4	BTx635	114	23.1	6.5
5	Serena	133	21.2	2.9
6	Lulu D	100	22.8	-1.1
7	RTx432	98	20.9	14.4
8	SC599-11E	104	26.7	21.4
Means		114 c‡	23.2c	11.4b
Sterile Single Crosses				
9	2*1	139	29.5	12.9
10	3*1	135	26.0	19.3
11	3*2	128	28.4	13.6
12	4*3	125	25.7	12.6
13	4*1	149	29.5	11.9
14	4*2	194	30.0	18.9
Means		145 b	28.2ab	14.9b
Fertile Single Crosses				
15	1*5	148	24.6	16.9
16	1*6	166	30.5	14.9
17	1*7	152	28.5	20.4
18	1*8	148	31.3	21.9
19	2*5	217	29.6	12.7
20	2*6	169	31.1	15.6
21	2*7	141	26.3	20.2
22	2*8	143	33.1	16.9
23	3*5	203	26.4	19.0
24	3*6	150	28.4	16.1
25	3*7	145	25.9	23.7
26	3*8	133	26.5	23.8
27	4*5	194	25.7	21.1
28	4*6	134	24.7	15.3
29	4*7	149	28.2	23.2
30	4*8	153	31.9	21.2
Means		159 a	28.3a	18.9a

Table 32. Continued.

Entry		Plant height	Panicle length	Panicle exsertion
Three-Way Crosses				
31	(2*1)*5	196	26.3	14.9
32	(2*1)*6	156	29.0	15.2
33	(2*1)*7	142	26.8	20.4
34	(2*1)*8	142	31.1	19.0
35	(3*1)*5	150	27.9	20.2
36	(3*1)*6	139	23.9	20.4
37	(3*1)*7	143	24.9	23.5
38	(3*1)*8	136	27.5	26.0
39	(4*1)*5	195	26.3	17.6
40	(4*1)*6	146	25.9	18.4
41	(4*1)*7	148	26.1	19.0
42	(4*1)*8	152	30.0	23.5
43	(3*2)*5	207	27.3	20.9
44	(3*2)*6	160	25.8	23.7
45	(3*2)*7	148	26.7	19.8
46	(3*2)*8	135	28.6	23.3
47	(4*2)*5	186	25.7	16.4
48	(4*2)*6	154	27.6	15.8
49	(4*2)*7	148	27.8	21.0
50	(4*2)*8	151	30.9	21.6
51	(4*3)*5	190	25.6	16.8
52	(4*3)*6	149	26.1	16.6
53	(4*3)*7	144	25.2	23.8
54	(4*3)*8	145	29.0	23.5
Means		157ab	27.2b	20.1a
Location means		150	27.0	17.9
LSD (0.05)		17	3.7	5.5

In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx631 single cross and Serena.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

three traits. The single-degree-of-freedom contrasts for parents vs hybrids, and for sterile single crosses vs fertile single and three-way crosses were significant for plant height and panicle exsertion, while fertile single crosses vs three-way crosses were significant only for panicle length.

The entry means for plant height, panicle length, and panicle exsertion at Alupe are shown in Table 32. Mean plant height ranged from 98 cm in RTx432 to 217 cm in the fertile single cross ATx631*Serena. The three-way cross (ATx3197*BTx631)*Serena (207 cm) and the fertile single cross ATx3197*Serena (203 cm) did not differ significantly from the tallest entry. The overall mean plant height was 150 cm. Comparisons of the plant height means using the LSD test indicated the sterile single crosses as significantly taller than the parental lines. They also had longer panicles. The sterile single crosses and the parental lines did not differ in their means for panicle exsertion. The fertile single crosses and the three-way crosses were significantly different for mean panicle length (Table 32).

Combined Analysis of Trials in Kenya 1992/93

The summary of the estimated mean squares from the combined analysis of variance for experiments in Kenya is presented in Table 33. The different characters were measured at varied numbers of locations, as indicated by the three different sets of degrees of freedom. The combined analysis of variance substantiated further the diversity of cultivars, earlier indicated in the individual environments analyses, and environmental response encountered. For all the attributes, significance was indicated for the environments, entries, and for the entries X environments interaction sources of variation. Partitioning of the variability due to entries into variation attributable to each of the type-groups (parental lines, sterile single crosses, fertile single crosses, and three-way hybrids) showed that the variations within parental lines and within fertile single crosses were significant for all the characters. Among single crosses, the variation was significant for all characters except threshing percentage, 1000-seed weight, and days to 50% anthesis. The variation within three-way crosses was significant for plant height, panicle length, and panicle exsertion.

Variability among the type-groups was highly significant for all the traits indicating the genetic variation among the types. Partitioning of the types sources of variation into orthogonal comparisons among type-groups showed that the parental lines vs hybrids was significant for all characters. Sterile single crosses vs fertile single and three-way crosses was significant for all traits except 1000-seed weight and panicle length. Fertile single crosses vs three-way crosses was significant only for grain yield. The interactions of each of the types with environments were significant with the exception of the parental lines X environments interaction for plant height,

Table 33. Mean squares in the combined analysis of variance for agronomic characters of sorghum parents, single, and three-way cross hybrids when stability parameters were estimated in Kenya during 1992/93.

Source	df	Mean Squares: Grain yield	Mean Squares: Grain yield	Mean Squares: Threshing percent	df	Mean Squares: 1000-seeds weight	Mean Squares: Days to 50% anthesis	df	Mean Squares: Plant height	Mean Squares: Panicle length	Mean Squares: Panicle exsertion
		kg ha^{-1}†	log_{10}	%		g	d		cm	cm	cm
Environments (Env)	3	3140.48**	0.51**	1432.24**	2	19.06*	1777.39**	4	6687.53**	182.32**	869.38**
Replicates/Env	8	65.90**	0.01**	36.59**	6	8.25*	7.62	10	205.65**	8.75**	23.70**
Entries	53	621.75**	0.19**	99.39**	53	12.63**	25.84**	53	3538.73**	27.90**	88.09**
Among Parents(P)	7	557.41**	0.32**	211.35**	7	17.47*	42.89**	7	758.69**	31.77**	141.68**
Among SSC	5	253.20	0.12*	32.69	5	10.07	8.79	5	1133.41**	13.48**	21.23*
Among FSC	15	739.87**	0.15**	64.22*	15	6.89	17.40**	15	3475.97**	24.89**	48.27**
Among TWC	23	231.08	0.04	40.95	23	7.81	4.89	23	2305.03**	14.95**	25.40**
Types	3	3790.67**	1.43**	573.32**	3	71.37**	217.26**	3	23806.42**	157.23**	754.19**
P vs H	1	7976.66**	3.41**	580.90**	1	205.25**	309.67**	1	62610.25**	459.55**	1564.34**
SSC vs (FSC+TWC)	1	2582.65**	0.54**	1101.10**	1	3.24	330.93**	1	8795.79**	7.81	693.71**
FSC vs TWC	1	812.71*	0.35**	37.97	1	5.63	11.17	1	13.24	4.32	4.52
Entries X Env	159	168.44**	0.05**	35.96**	106	5.95**	4.41**	212	213.66**	2.42**	8.99**
Among P X Env	21	29.50*	0.05	44.86**	14	8.46**	7.39**	28	57.95	2.84*	13.26**
Among SSC X Env	15	77.50**	0.03	35.30**	10	5.41	4.70**	20	150.90**	3.25*	10.48**
Among FSC X Env	45	219.97**	0.07**	39.57**	30	4.87	6.76**	60	233.71**	2.35*	9.13**
Among TWC X Env	69	173.95**	0.03	29.80**	46	6.15*	1.71	92	252.70**	1.91	6.79*
Types X Env	9	344.25**	0.13**	45.41**	6	4.95	5.95**	12	282.09**	4.30**	12.72**
P vs H X Env	3	620.30**	0.839**	104.20**	2	5.14	1.94	4	295.37**	4.64*	21.10**
SSC vs (FSC+TWC) X Env	3	143.31**	0.20**	29.47	2	6.92	13.31**	4	373.41**	2.98	6.76
FSC vs TWC X Env	3	269.14**	0.16**	2.55	2	2.80	2.60	4	177.47*	5.27*	10.29*

Table 33. Continued.

Source	df	Mean Squares: Grain yield	Grain yield	Threshing percent	df	Mean Squares: 1000-seed weight	Days to 50% anthesis	df	Mean Squares: Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}†	log_{10}	%		g	d		cm	cm	cm
Env(*l*)	1	9421.45**	1.51**	4296.72**	1	38.11*	3554.78**	1	26750.12**	729.27**	3477.51**
Entries X Env(*l*)	53	167.40	0.05*	62.01**	53	6.24	6.53**	53	487.44**	2.01	12.88*
Among P X Env(*l*)	7	56.82	0.05	31.55	7	4.56	11.59**	7	122.99	1.59	23.83**
Among SSC X Env(*l*)	5	48.17	0.03	55.71*	5	4.37	4.20	5	99.37	5.83*	4.40
Among FSC X Env(*l*)	15	156.08	0.06*	69.09**	15	5.20	11.07**	15	600.86**	3.20	21.09**
Among TWC X Env(*l*)	23	164.95**	0.03	70.65**	23	5.26	2.33	23	572.02**	0.75	6.43
Type X Env(*l*)	3	699.55**	0.21**	42.05	3	6.71	8.12*	3	769.15**	0.30	33.15**
P vs H X Env(*l*)	1	1606.29**	0.48**	61.73	1	4.97	3.20	1	710.93*	0.01	73.15**
SSC vs (FSC+TWC) X Env(*l*)	1	93.86	0.00	64.42	1	13.84	17.27**	1	988.70**	0.82	2.03
FSC vs TWC X Env(*l*)	1	398.50	0.16*	0.00	1	1.33	3.90	1	607.82*	0.08	24.27
Pooled deviations	108	165.82**	0.03	22.50**	54	6.47*	2.25	162	120.14**	2.51**	7.55**
Parents	16	27.41*	0.06*	58.44**	8	11.55**	2.86	24	48.44	3.51**	11.83**
SSC	12	97.26**	0.04	22.28*	6	4.69	5.58*	18	159.46**	2.53	11.55**
FSC	32	241.04**	0.07**	23.75**	16	4.48	2.49	48	110.24**	2.15	4.91
TWC	48	178.96**	0.00	9.75	24	6.54*	1.05	72	140.80**	2.41	6.89**
Pooled error	424	15.37	0.03	11.81	318	3.55	2.23	530	53.85	1.74	4.01
CV%		21.53	2.73	8.31		12.44	3.53		8.21	8.24	25.32

† Mean squares equal 10^4 times the column values.
*, ** Significant at 0.05 and 0.01 probability levels, respectively.
SSC, FSC, and TWC: Sterile single cross, fertile single cross, and three-way cross hybrids, respectively.

sterile single crosses X environments and fertile single crosses X environments interactions for 1000-seed weight, and three-way crosses X environments interaction for days to 50% anthesis and panicle length. Interactions of types X environments displayed a similar pattern of significance as was shown in the variation among types, except that 1000-seed weight was not significant in the interaction.

Significance was shown for the interaction of parents vs hybrids X environment for all the characters except 1000-seed weight and days to 50 % anthesis. Sterile single crosses vs fertile single and three-way crosses X environments interaction was significant for grain yield, days to 50% anthesis and plant height. Fertile single crosses vs three-way crosses X environments interaction was significant for grain yield, plant height, panicle length, and panicle exsertion.

Mean yields of all entries ranged from 2341 kg/ha at Kakamega during the long rainy season to 3795 kg/ha at Kakamega during the short rainy season. Similarly a wide range of environmental conditions was reflected by the means for threshing percentage (64% at Kakamega long season to 76% at Kibos), days to 50% anthesis (67 d at Kibos to 78 d at Kakamega short season), plant height (141 cm at Kiboko to 172 cm at Kibos), panicle length (25.5 cm at Kakamega short season to 28.1 cm at Kiboko), and panicle exsertion (8.3 cm at Kakamega long season to 17.9 cm at Alupe). Little variation in environments was indicated for 1000-seed weight, with the means ranging from 25.5 g to 26.9 cm at Kakamega during the short and long rainy seasons, respectively. Coefficients of variation for grain yield ranged from 16 to 25%, with over 20% obtained at Kibos and Kiboko. C.V.'s for the yield components and other agronomic characters ranged from 2 to 14% but mostly under 10%, except for panicle exsertion which had as high as 37% C.V. at Kakamega during the long rainy season.

The overall environments means for each entry are presented in Table 34. The mean grain yield for the entries ranged from 829 kg/ha in the parental line BTx631 to 6265 kg/ha in the fertile single cross ATx635*Serena. The best yielding three-way cross overall environments was (ATx635*BTx630)*Serena (4919 kg/ha). In all environments, the fertile single crosses and the three-way crosses were the most productive types. The entries had an overall mean of 3153 kg/ha with the different type means being 1696 kg/ha for parental lines, 2439 kg/ha for sterile single crosses, 3276 kg/ha for fertile single crosses, and 3736 kg/ha for three-way hybrids. Overall environments, sterile single crosses outyielded parental lines significantly (LSD test). Walsh and Atkins (1973) and Hookstra and Ross (1982) have reported the superiority of sterile single crosses over sterile (A-) lines as seed parents. In this study the parental lines included for evaluations were fertile maintainer (B-) and restorer (R-) lines, but the sterile F_1 hybrids still indicated superiority. This therefore supports the recommendation by Hokstra and Ross (1982) for the use of F_1 sterile parents in hybrids if acceptable high performing hybrids are identified.

Table 34. Means for agronomic characters in sorghum parents, single, and three-way-cross hybrids at five locations in Kenya during 1992/93.

Entry†	Grain yield	Threshing percent	1000-seeds weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	$kg\ ha^{-1}$	%	g	d	cm	cm	cm
Parents							
1 BTx630	840	55	24.7	74	132	26.0	9.0
2 BTx631	829	64	22.0	74	119	27.0	6.3
3 BTx3197	1777	71	25.2	76	120	22.0	11.7
4 BTx635	1140	72	21.0	79	119	23.7	8.0
5 Serena	4221	79	26.8	73	138	21.4	3.0
6 Lulu D	2578	73	20.0	78	107	24.3	-0.9
7 RTx432	905	64	25.7	72	103	24.3	9.8
8 SC599-11E	1278	65	23.0	72	106	28.9	16.6
Means	1696 d‡	68 b	23.5b	76 a	118c	24.7b	7.9c
Sterile Single Crosses							
2*1	1213	63	28.2	79	133	30.6	6.4
3*1	2689	69	28.0	75	142	26.7	12.1
3*2	2591	69	26.0	74	130	27.9	10.0
4*3	3654	68	27.2	75	138	27.7	10.7
4*1	2137	62	24.8	78	159	30.9	10.3
4*2	2351	66	23.7	77	167	29.6	11.8
Means	2439 c	66 b	26.3a	77 a	145b	28.9a	10.2b
Fertile Single Crosses							
1*5	3276	75	27.4	72	196	27.7	13.7
1*6	3280	71	26.8	73	164	29.2	13.6
1*7	2610	74	27.8	71	147	29.1	13.2
1*8	3391	75	25.3	72	151	31.2	16.4
2*5	5415	78	28.7	71	218	28.8	9.8
2*6	2827	64	26.0	74	165	30.3	12.8
2*7	2527	68	25.1	74	143	39.3	11.3
2*8	1957	71	25.0	76	146	32.4	12.3
3*5	5517	78	29.8	68	208	26.1	17.0
3*6	1428	67	26.1	76	148	26.0	17.3
3*7	3410	72	28.1	69	146	26.3	19.1
3*8	1923	73	26.3	71	137	26.7	20.6
4*5	6265	78	28.3	70	200	26.2	16.6
4*6	3324	73	25.9	74	142	25.5	13.0
4*7	2909	73	29.5	74	149	28.9	17.4
4*8	2354	74	26.5	72	156	32.1	18.8
Means	3276 b	73 a	27.0a	72 b	163a	28.5a	15.2a

Table 34. Continued.

Entry	Grain yield	Threshing percent	1000-seeds weight	days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
	kg ha^{-1}	%	g	d	cm	cm	cm
Three-Way Crosses							
(2*1)*5	3754	74	27.1	71	206	27.2	11.8
(2*1)*6	2417	72	26.5	75	157	28.4	13.3
(2*1)*7	2634	73	28.1	72	146	28.8	12.9
(2*1)*8	3164	71	25.7	74	144	31.4	13.8
(3*1)*5	4410	75	30.1	70	180	27.9	14.8
(3*1)*6	4395	71	26.7	71	153	26.4	15.8
(3*1)*7	4616	73	29.5	70	149	26.3	17.6
(3*1)*8	3198	76	24.3	71	139	29.3	19.2
(4*1)*5	4919	77	29.1	71	200	25.9	13.7
(4*1)*6	3736	71	24.4	73	153	27.4	13.6
(4*1)*7	3166	70	26.6	72	154	27.9	15.2
(4*1)*8	2863	72	26.0	72	174	29.8	19.1
(3*2)*5	4289	75	28.1	70	196	28.3	16.9
(3*2)*6	4357	70	27.5	72	161	27.6	16.8
(3*2)*7	4210	78	26.0	71	149	26.8	15.4
(3*2)*8	2764	75	26.7	71	138	29.3	18.9
(4*2)*5	4774	78	26.5	70	205	26.2	13.3
(4*2)*6	4232	67	25.2	73	153	28.6	12.6
(4*2)*7	2767	71	26.6	74	156	29.1	15.3
(4*2)*8	4170	78	23.7	72	155	32.0	17.5
(4*3)*5	4323	78	27.1	71	193	25.5	14.9
(4*3)*6	3823	75	24.3	71	147	27.3	13.9
(4*3)*7	2796	71	26.6	71	153	28.0	16.8
(4*3)*8	3879	79	26.1	72	151	31.2	19.3
Means	3736 a	74 a	26.6a	72 b	186a	28.2a	15.5a
General means	3153	72	26.2	73	154	27.8	13.7
LSD(0.05)	545	4.8	3.0	2.4	9.1	1.6	2.5

† In this table, the parents in a particular cross are identified by number; e.g., 2*1 is a single cross of ATx631 and BTx630, while (2*1)*5 represents a three-way cross between ATx631 by BTx631 single cross and Serena.

‡ Type means in the same column followed by same letter are not significantly different according to LSD (0.05).

The three-way hybrids significantly outyielded the fertile single crosses overall environments. Mean yields of the three-way crosses were significantly higher than the fertile single crosses in one of the four environments, slightly higher in two other environments, and slightly lower in the remaining environment. Ross (1969) reported that the mean yields of the two types of hybrids did not differ significantly, but significant differences were obtained in two of the four years; three-way hybrids yielded less than the single cross in a poor year, but were more productive in a year characterized by high yields. Similar trends were observed in the current study, the three-way hybrids outyielded the fertile single crosses in the better environments, Kibos and Kakamega short season. Jowett (1972), Patanothai and Atkins (1974), and Walsh and Atkins (1970) reported equivalent mean yields for fertile single crosses and three-way crosses. A fertile single cross was the highest yielding entry in two of the four environments, a three-way hybrid in one, and a sterile single cross yielded the most in one environment.

The fertile single crosses and the three-way hybrids indicated similar performances for all the other yield components and agronomic characters, outperforming the male-sterile single crosses in all characters except 1000-seed weight and panicle length which were not significantly different. The two types of fertile hybrids also outperformed the parental lines in all the traits. Sterile single crosses were superior to the parental lines in all the characters except threshing percentage, for which they did not differ significantly (LSD test).

Stability Analysis of Trials in Kenya

New cultivars developed are expected to combine an improved yield potential, stability and to take advantage of favorable environments. Stability of performances of the type-groups across environments was assessed by comparing deviation mean squares from regression (Table 35), which measure the residual variation at each environment not accounted for by the environmental effect. The requirement of a cultivar to have greater responsiveness to better environments was assessed by regression of a cultivar trait on an environmental index, where a responsive cultivar to a better environment will have a coefficient of 1.0 or greater. A regression coefficient larger than 1.0 may indicate either a better than average response to high-yield environments or a worse than average response to low-yield environments. A desirable, stable cultivar is one having a mean yield higher than the average yield of all cultivars under test, regression coefficient close to unity, and small deviations from regression, possibly close to zero (Eberhart and Russell, 1966).

Segments of the analysis of variance when stability parameters are estimated are given for the characters in Table 33. The data for grain yield were analyzed for stability using both the arithmetic scale and the logarithmic scale. Faris et al (1981) reported better data interpretation

Table 35. Stability parameters for agronomic traits in sorghum parents, single, and three-way cross hybrids in five environments in Kenya during 1992/93.

Entry†	Grain yield		Log_{10} yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
Parents																
1 BTx630	0.21*	12.04	0.43	0.05	1.28	15.74	2.81	0.44	0.93	3.65	0.77	62.35	1.25	-0.13	1.17	0.84
2 BTx631	-0.07**	-7.52	-0.38	-0.01	1.30	7.88	-0.45	-3.02	1.05	-1.36	1.49	77.51	1.47	12.51**	1.25	20.23
3 BTx3197	-0.48**	34.82*	-0.83	0.00	0.78	0.14	4.53**	-3.52	1.56**	0.44	0.00**	-41.50	0.66	0.67	0.54	-0.29
4 BTx635	-0.90**	23.93	-3.11*	0.05	-0.11**	0.80	3.36*	-2.84	0.95	0.46	0.64	-30.31	0.72	-0.79	-0.21**	11.41**
5 Serena	0.82	-4.43	0.61	-0.03	-0.30**	37.19*	4.65**	-2.76	0.34	-1.79	0.74	-23.35	1.40	-0.43	0.47	16.67**
6 Lulu D	0.47**	-10.19	0.67	-0.03	0.53	5.83	-2.36*	-1.93	0.96	2.19	0.95	-42.61	0.86	-0.96	0.71	5.42*
7 RTx432	-0.37**	27.17	-1.32	0.10	1.26	285.26**	1.97	79.72**	1.08	-0.18	0.14**	-21.01	0.60	3.69*	0.85	-2.31
8 SC599-11E	0.40	20.54	1.03	0.07	0.96	68.63**	0.42	-2.12	1.71**	1.64	0.14**	-24.35	1.10	-0.42	0.44	7.61*
Sterile Single Crosses																
2*1	0.10*	13.51	0.24	0.04	0.04	44.22**	5.11*	-1.44	0.74	2.64	0.57	-0.85	1.27	0.52	1.48**	0.28
3*1	0.98	156.16**	1.04	0.04	-0.43**	-2.34	3.07	3.80	0.73**	-2.06	0.53**	-34.73	0.29*	0.60	1.07	5.01
3*2	0.80	108.90**	1.09	-0.01	1.07	6.04	1.02	-2.73	1.14**	-2.22	0.48	-9.63	0.75	0.30	1.15	13.37**
4*3	1.12	78.20**	0.98	-0.02	1.25	10.97	4.06**	-3.54	0.58**	-1.64	0.43	6.42	0.99	-0.40	0.84	0.42
4*1	1.69*	1.48	3.27**	-0.02	1.84**	-3.74	-2.22	0.60	1.05	-1.36	1.29	-21.23	1.00	1.13	0.86	1.96
4*2	0.67	133.11**	0.69	0.02	0.47	7.67	4.17	10.17*	0.52	24.72**	-0.11	693.71**	2.25	4.82*	1.38	27.38**
Fertile Single Crosses																
1*5	1.00	55.12*	0.94	-0.01	0.02**	-2.98	-2.51	-1.26	0.65*	-0.31	2.97	662.06**	1.42	1.12	0.87	-2.39
1*6	2.25**	24.28	3.39**	-0.01	2.56**	-5.74	2.37	-0.33	0.81	-1.16	1.16	-27.12	0.80	0.91	0.88	4.54
1*7	-0.53	229.24**	-1.19	0.09*	0.43	29.65*	0.69	1.08	1.25**	-1.95	0.18**	-35.25	1.61**	-1.23	1.80**	-2.14
1*8	1.00	23.17	0.99	-0.02	0.78**	-11.74	-2.91**	-3.54	0.89**	-2.23	-0.48**	28.40	1.57	0.36	1.23	-2.93
2*5	1.82	430.95**	0.97	0.01	-0.24**	-11.59	4.38**	-3.55	0.89**	-2.23	2.82**	160.47**	0.78	-0.72	1.12	3.75
2*6	1.30	159.19**	2.72	0.03	2.95	86.37**	1.00	-3.36	1.10	-1.39	0.92	-6.06	1.08	9.23**	0.80	5.04
2*7	0.86	149.11**	2.19	0.03	1.76	6.85	-5.11**	-1.44	1.28	5.26	0.25	45.67	1.34	2.60	1.98**	-0.37
2*8	0.07	171.83**	0.59	0.05	1.83	27.78*	-2.62	8.26	0.60**	-0.82	-0.64**	152.30**	1.25	0.25	1.26	5.80
3*5	0.61	94.56**	0.33	-0.02	-0.05**	-11.60	2.92	5.17	1.39**	-1.25	2.55**	85.89	0.96	-1.03	0.61	0.01
3*6	-1.02**	-14.36	0.45**	-0.02	0.79	1.50	0.53	21.21**	0.19	10.36*	0.64	-13.51	-0.12*	2.63	-0.35**	2.20
3*7	1.52	492.40**	1.05	0.04	0.89**	-11.71	2.76**	-3.53	1.45	6.74	0.45**	-39.05	0.53**	-1.70	0.62	-0.80

Table 35. Continued.

Entry†	Grain yield		Log_{10} yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
Fertile single cosses (cont'd)																
3*8	0.29	229.95**	-0.05	0.13**	1.31	-4.22	2.78	2.55	1.49**	-2.05	0.57*	-29.29	0.87	-1.65	0.09**	2.46
4*5	2.43	288.47**	1.35	-0.02	0.14	-11.37	2.52	-1.14	1.03	-2.05	2.05**	22.77	0.73**	-1.66	1.26	2.24
4*6	0.97	884.34**	-0.13	0.20**	1.48	14.65	1.02	1.13	0.34**	-1.63	0.56**	-38.79	0.18*	0.23	0.79	-1.61
4*7	1.78	68.05**	2.03	0.00	1.26	83.92**	3.26	-3.43	0.59	-2.19	0.71	-15.19	1.14	-1.48	1.22	-2.79
4*8	0.40	324.42**	0.20	0.13**	1.72	11.24	2.71	-2.89	1.00	1.04	0.27**	-51.02	1.40*	-1.24	0.73	1.32
Three-way Crosses																
(2*1)*5	0.70	45.51*	0.61	-0.02	-0.53**	-0.33	1.95	5.40	0.94	-1.39	2.97**	-44.94	0.76	-0.82	1.35	3.44
(2*1)*6	-0.51*	72.91**	-0.66	0.00	0.75	-6.73	5.31	1.08	0.90	-0.72	0.23	50.83	0.71	0.33	1.19	6.88*
(2*1)*7	0.86	203.35**	1.01	0.01	1.26	11.54	-2.30	8.35	1.00	-2.11	0.44	-10.70	1.08	-0.32	1.75*	2.50
(2*1)*8	0.89	234.96**	0.59	0.02	0.44*	-7.86	-0.97**	-3.55	0.78**	-2.02	1.02	0.66	0.95	-0.10	1.83**	1.96
(3*1)*5	0.59	211.24**	0.43	-0.01	-0.31**	-1.01	2.27**	-3.54	0.96	-1.79	3.80**	84.97	0.67	0.20	0.81	-0.34
(3*1)*6	3.08**	43.74*	2.78**	-0.02	1.86**	-6.08	4.88	-3.47	0.98	-2.21	1.09	65.33	0.99	3.20*	1.05	1.19
(3*1)*7	2.49	889.04**	2.80	0.09*	3.00**	19.98	3.32	-1.90	1.27**	-2.07	1.07	-17.13	0.88	0.01	1.00	7.30*
(3*1)*8	1.32	34.40*	1.75	-0.02	1.22	3.00	-4.15	17.21*	1.47**	-0.41	0.49**	-37.02	1.22	-0.69	0.99	6.43
(4*1)*5	0.84	315.24**	0.57	0.01	0.28**	-9.54	3.87	2.42	0.79	-1.38	3.29**	15.33	0.93	1.00	0.84	8.98*
(4*1)*6	2.54	132.41**	3.19**	-0.01	2.53**	5.15	-4.06**	-3.54	0.92	-1.70	1.13	-35.94	0.66	-0.25	1.08	-1.96
(4*1)*7	1.39	109.51**	2.32	0.01	1.53*	-7.43	0.10	-2.15	1.11	-1.62	0.56**	-47.69	1.18	-0.80	1.03	-1.58
(4*1)*8	1.47	268.18**	2.14	0.02	1.81**	-9.44	-3.83**	-2.35	1.07	4.69	0.64	1412.77**	1.26	1.75	1.36	0.52
(3*2)*5	1.32	367.18**	0.97	0.00	-0.01	15.00	0.43	-0.05	1.24	1.36	2.71	676.10**	1.01	7.80	1.02	-0.43
(3*2)*6	3.26**	82.77**	3.16**	-0.02	1.85	-5.17	1.16	2.24	0.92	-1.70	0.71	-32.02	1.31	1.35	1.33	-1.45
(3*2)*7	0.85	-6.02	0.72*	-0.03	0.08**	-11.58	0.89	-1.44	1.14	-1.54	0.30*	-3.43	1.10	1.64	1.16	3.74
(3*2)*8	0.73	63.97**	1.26	-0.01	1.96	39.58*	4.78	-0.98	1.30**	-1.54	0.31**	-43.42	0.93	0.93	0.99	6.99*
(4*2)*5	0.21*	4.23	0.20	-0.03	0.32**	-11.65	5.47	21.21**	0.87**	-2.20	2.01	153.64**	1.15	-1.54	1.20	2.57
(4*2)*6	3.07*	166.63**	3.45*	0.01	2.17**	-10.91	-2.82**	-2.41	0.85	1.03	0.65	-35.93	1.24	-1.45	1.28	2.27
(4*2)*7	1.33	172.08**	1.88	0.00	1.82**	-11.68	0.07	-0.81	0.85**	-2.10	1.16	41.05	1.35	-0.63	1.58**	-3.02
(4*2)*8	1.69	107.75**	1.51	-0.02	0.99	-11.05	-5.38**	-3.30	1.10	-1.96	0.33**	-28.94	0.87	0.39	0.72	-0.58
(4*3)*5	0.57	122.06**	0.40	-0.02	-0.12**	-9.89	1.87	-1.06	1.02	-0.60	2.96**	-10.09	1.10	3.38*	0.68	10.99*

Table 35. Continued.

Entry†	Grain yield		Log_{10} yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}	b_i	S^2_{di}
Three-way crosses (cont'd)																
(4*3)*6	2.64**	-11.18	0.10	-0.03	1.21	-3.18	-3.83**	-2.35	1.09	-2.02	0.74	-41.59	0.39*	-0.73	0.96	-2.89
(4*3)*7	1.32	238.82**	1.72	0.01	1.51	-11.74	0.12	-3.04	1.25**	-2.19	1.71	18.44	1.07	1.11	1.34	9.81*
(4*3)*8	1.19	57.50**	1.17	-0.02	0.82	-8.44	0.93	0.81	1.35**	-2.23	0.68	-43.44	1.08	1.03	0.56	5.68
Types over all																
Parents	0.01**	12.04*	-0.37	0.03*	0.71	46.63**	1.87	8.00**	1.07	0.63	0.61	-5.41	1.01	1.77**	0.65	7.82**
Sterile singles	0.89	81.89**	1.22	0.01	0.71	10.47*	2.53	1.14	0.79	3.35*	0.53	105.46**	1.09	0.79	1.13	7.54**
Fertile singles	0.92	225.67**	0.80	0.04**	1.10	11.94**	0.86	0.93	0.97	0.26	0.93	56.39**	0.97	0.41	0.93	0.90
Three-ways	1.41	163.59**	1.53**	-0.03	1.10	-2.06	0.42	2.99**	1.05	-1.18	1.29	86.95**	1.00	0.67	1.13	2.88**

† Parents in the crosses are identified by respective numbers.
*, ** Significantly different from 1 for regression coefficient (b_i) and from 0 for mean square deviations (S^2_{di}) at 0.05 and 0.01 levels of probability, respectively.

coming from log transformed data. A similar situation was encountered by Jowett (1972), who indicated that when very wide differences were obtained in yielding ability among entries, the low yielding entries might be constrained by the additive nature of the model on the arithmetic scale. Under a logarithmic model the situation changes because the effects which are multiplicative on the original scale of measurements become additive on the logarithmic scale.

The analysis of variance indicated that for grain yield a large proportion of the total environmental and entries X environments variation was attributable to differences between environments (linear) and due to differences among the fitted regression lines. Testing for genetic differences among the entries for their regression upon the environmental indices indicated that on the arithmetic scale, entries X environments (linear) was not significant for yield. However, significance was indicated on the logarithmic scale. Similarly significance of entries X environments (linear) as tested against the pooled deviation was revealed for all the other characters except for 1000-seed weight and panicle length. Therefore, the linear model retained considerable predictive value for the entries concerned.

Analogous tests for each of the four type-groups for grain yield showed genetic differences for the environments (linear) interaction with only three-way crosses on the arithmetic scale, but only fertile single crosses on the logarithmic scale. Threshing percentage indicated significance for the interaction of each of the type-groups with environments (linear). The among types X environments (linear) mean squares for grain yield, days to 50% anthesis, plant height, and panicle length, were significant indicating that the different types differed genetically in their response to varying environments. The single-degree-of-freedom partitioning of the interaction of environments (linear) with each of the type group comparisons were significant for grain yield on the arithmetic scale in parents vs hybrids X environments (linear) and on the logarithmic scale in fertile single crosses vs three-way crosses X environments (linear). The linear components of interactions were otherwise nonsignificant in most cases and only explained a small portion of the interactions. Hence, the deviation mean squares were as large as the total interaction mean squares.

Pooled deviations mean squares were significant for all the characters except for grain yield on the logarithmic scale. On both the scales for grain yield the fertile single crosses indicated the largest deviation mean squares. Under the logarithmic scale the deviation mean squares for sterile single crosses and three-way crosses were nonsignificant with the latter indicating the smallest deviation mean squares. Similarly, the three-way crosses had the smallest and nonsignificant deviation mean squares for threshing percentage. These results indicate the three-way crosses to be stable for grain yield and threshing percentage.

Regression coefficients and mean squares of deviations from regression for each entry, and for the individual type-groups of entries are given in Table 35. The regression coefficient for three-way crosses was greater than 1.0, indicating their responsiveness to improving environments, coupled with their mean grain yield and mean threshing percentage which were higher than the averages overall the test environments, three-way crosses were considered most stable under conditions of this study. Although the sterile single crosses also indicated S^2_{di} near zero and b_i near 1.0, their mean yield was far below the average. Fertile single crosses indicated instability, with a significant S^2_{di} for grain yield on both scales. Three-way crosses also indicated stability for days to 50% anthesis and panicle length. Increasing stability with increasing cultivar heterogeneity has been reported in sorghum (Jowett, 1972; Patanothai and Atkins, 1974; Reich and Atkins, 1970), maize (Weatherspoon, 1970), and Rye (Baker et al., 1982).

Within-Plot variability in Trials in Kenya

Within-plot variability, measured the standard deviations for plant height, panicle length, and panicle exsertion for the trials in Kenya were as shown in Appendix A, Table A3. The variability in the hybrids was high especially for plant height more than in the parents. The sterile single crosses had less variability than the fertile single crosses and three-way crosses. The most important hybrids for commercial production, fertile single crosses and three-way crosses, had near similar variabilities in most instances. Though the limits of variability that might be tolerated would differ among sorghum growers, the problem of excessive variability in Kenya might not be as pronounced a desirability factor as would be the case in Texas. The differences stem from the fact that, in Texas combine harvesting of sorghum is routine in commercial production, requiring the desirability for shorter and more uniform (for height and maturity) cultivars; in Kenya harvesting of sorghum is still an entirely manual operation by hand so some variability is tolerated. Therefore, in Kenya within-plot variability of a sorghum crop might not be a primary issue of consideration at this moment. The variability could still be controlled to an appreciable level by selection of appropriate parents (Rosenow, 1968; Stephen and Lahr, 1959).

Heterosis (High-Parent) for Grain Yield in Trials in Kenya

The percentage high-parent heterosis values for mean grain yield for trials in Kenya are presented in Appendix B, Table B2. The amount of heterosis depended on the location and the type of hybrid. The percentage of high parent heterosis in individual crosses ranged from -61.1 to 450.5%. It was most appropriate to examine the results from each location separately because the mean yields overall entries for the four locations were widely different, and the cultivars indicated a significant interaction with environments. The large entries X environments interaction resulted in the heterosis values calculated combined overall environments to indicate nonsignificance according to the single-degree-of-freedom comparisons.

Higher heterosis expression was indicated at Kiboko than at the other locations. Significant negative heterosis were indicated in some of the crosses of the hybrid-types for grain yield. Among the sterile single crosses, ATx635*BTx3197 and ATx3197*BTx631 had significant and positive high-parent heterosis, though the latter indicated significant negative heterosis at Kakamega during the long rainy season. High-parent heterosis in the sterile single cross is of a great advantage to the seed producers in reducing the cost of producing three-way hybrid seed, and such reduction in cost should be reflected in the final hybrid seed price to the farmer.

Among fertile single crosses, consistency in positive high-parent heterosis was indicated by the crosses ATx630*RTx432, ATx630*SC599-11E, ATx631*Serena, ATx635*RTx432, and ATx635*SC599-11E. High-parent heterosis also was indicated by three-way cross hybrids, with (ATx635*BTx631)*SC599-11E showing significant and positive high-parent heterosis at all the locations. Serena, a local cultivar, was high yielding at all the locations and therefore low nonsignificant heterotic values were indicated in most of the crosses involving Serena. Again, as was the case in the Texas trials, this study indicated a tendency for high percentage heterosis to be associated with hybrids whose parents were comparatively low yielding.

Genetic Effects for Trials in Kenya

Segments of the analysis of variance when genetic effects for grain yield and other agronomic characters were estimated are presented in tables that follow. The entries sources of variation were partitioned into variation attributable to various genetic effects as specified in the genetic model, and the deviations (Gardner and Eberhart, 1966). The deviations included reciprocal effects, epistasis and any other deviations from the genetic model. Deviation mean squares were used to test the significance of the parental and heterosis effects, whereas the experimental error, in the case of individual locations analyses, and entries X environments interaction in the combined analysis, were used to test the significance of the deviations from the full genetic model.

Variations in mean grain yield among entries, at the individual locations, were primarily attributable to parental effects (Table 36). Overall heterosis was not significant for grain yield at all the environments except Kiboko. Of the components of overall heterosis for grain yield, only the average heterosis was significant at all the locations except for Kakamega during the long rainy season, where average heterosis indicated nonsignificance. Line and single cross specific heterosis were not significant for grain yield at all the locations. Deviations from the full model was

Table 36. Mean squares for genetic effects (fixed model) for grain yield and threshing percent at four sites in Kenya during 1992/93.

		Grain yield (kg ha^{-1})†				Threshing percent (%)			
Source	df	Kibos	Kiboko	Kakamega (L)	Kakamega (S)	Kibos	Kiboko	Kakamega (L)	Kakamega (S)
Parents	7	667.96**	210.05*	765.25**	690.00	89.42**	84.18**	417.10**	23.90**
Heterosis‡	22	314.76	225.03**	54.12	453.52	26.79**	92.51**	54.76	7.55*
h	1	4309.92**	2511.16**	96.16	3936.75**	140.84**	745.19**	10.51	45.89**
h	7	82.78	100.93	107.35	99.90	18.72	128.77**	98.41	13.68**
s	14	145.37	123.78	24.50	381.52	22.67*	27.76	36.09	1.75
Deviations	24	223.36**	77.89ns	65.87**	481.16**	8.40	17.56	54.14	3.02
Error	106	68.55	48.81	13.48	53.59	25.48	59.62	42.23	14.36

*, ** Significant at the .05 and .01 probability levels, respectively.

† Multiply mean squares for grain yield by 10^4.

‡ h = average heterosis of the single crosses; h = specific heterosis of a line; s = specific heterosis in a single cross.

L and S in parenthesis indicate long rainy season and short rainy season at the same site.

significant at all the locations, except for Kiboko. The mean squares for parents were highly significant for threshing percentage at all the locations (Table 36). Except for Kakamega, during the long rainy season, where nonsignificance for threshing percentage was indicated for overall heterosis and its components, the variation due to heterosis was significant at all the locations. The line specific heterosis was not significant at Kibos. Specific cross heterosis for threshing percentage was not significant at Kiboko and Kakamega, during the short rainy season. Deviations from the full genetic model were nonsignificant for threshing percentage in all the analyses.

The variation among cultivars for 1000-seed weight was attributed to both the parental and heterosis effects at Kibos (Table 37). At Kakamega, during the short rainy season, the parents' effects were not significant, while during the long rainy season overall heterosis was not significant. In both the seasons at Kakamega the specific single cross heterosis effect was not significant for 1000-seed weight. The deviations mean squares for 1000-seed weight were not significant at all the locations. Days to 50% anthesis (Table 37) indicated highly significant mean squares for both parental and overall heterosis effects at each of the locations. Nonsignificance was indicated for the components of heterosis except at Kakamega, during the long rainy rains, where significance was indicated for specific line and single cross heterosis. The deviations from the full model for days to 50% anthesis were nonsignificant in all instances.

The mean squares for the genetic effects for plant height, panicle length and panicle exsertion at each location are shown in Table 38. Parental and overall heterosis effects were significant at all the locations except Kakamega, during the long rainy season, where overall heterosis was not significant. Among the components of overall heterosis, average heterosis accounted for the highest percentage and was significant in all the instances.

The genetic effects in the combined analysis of trials in Kenya, for all the characters studied are shown in Table 39. Additive (parents) effects were highly significant for all the characters, indicating importance of additive gene action in the expression of these characters. Overall heterosis also was significant for all characters. The highly significant heterosis effects implied that nonadditive gene action also was important. Of the components of overall heterosis, average heterosis was most important, and was significant in all characters. Line specific heterosis was found to be significant for threshing percentage, plant height, and panicle exsertion. Single cross specific heterosis was significant for plant height and panicle exsertion only. Deviations from the full model in the combined analysis was significant only for grain yield, indicating epistasis to be of importance in the expression of this trait. In general, similar trends were observed in combined as was in the individual locations analyses.

Conventional and genetic analyses in the present study provided information on the type of genetic effects present in the fixed set of cultivars. Given the entries included in this study,

Table 37. Mean squares for genetic effects (fixed model) for 1000-seed weight and days to 50% anthesis at three sites in Kenya during 1992/93.

		1000-seed weight (g)			Days to 50% anthesis (d)		
Source	df	Kibos	Kakamega (L)	Kakamega (S)	Kibos	Kakamega (L)	Kakamega (S)
Parents	7	20.73**	33.29**	3.29	66.20**	32.15**	28.97**
Heterosis†	22	8.48**	9.39	9.85**	16.09**	8.17**	9.88**
h	1	61.60**	40.36**	118.46**	102.65**	120.89**	162.15**
h	7	8.88**	4.13	8.07*	13.72	2.77**	3.65
s	14	4.48*	9.80	2.98	11.09	2.82**	2.11
Deviations	24	1.86	7.39	2.83	5.72	0.75	1.64
Error	106	4.85	14.96	12.16	12.07	2.50	5.47

*, ** Significant at the .05 and .01 probability levels, respectively.

† h = average heterosis of the single crosses; h = specific heterosis of a line; s = specific heterosis in a single cross.

L and S in parenthesis indicate long rainy season and short rainy season at the same site.

Table 38. Mean squares for genetic effects (fixed model) of Plant height, panicle length and panicle exsertion at five sites in Kenya during 1992.

		Plant height (cm)					Panicle length (cm)		
Source	df	Alupe	Kibos	Kiboko	Kakamega (L)	Kakamega (S)	Alupe	Kibos	Kiboko
Parents	7	1952.23**	7085.21**	503.74**	3433.41**	1968.47**	25.20**	43.19**	20.56**
Heterosis†	22	947.63**	1720.81**	715.10**	936.15*	720.47**	7.89**	6.45**	9.76**
h	1	11929.87**	20599.66**	11596.37**	11990.52**	8985.17**	132.07**	57.25**	130.17**
h	7	494.38**	2090.67**	366.17*	755.23	531.53**	0.27	3.21	5.87
s	14	389.80**	187.39*	112.32	237.02	224.37**	2.83	4.44**	3.10
Deviations	24	86.53	88.19	113.84	416.09**	19.02	2.06	1.45	3.23
Error	106	106.56	90.05	432.11	121.74	57.33	5.18	3.09	6.21

		Panicle length (cm)		Panicle exsertion (cm)				
Source	df	Kakamega (L)	Kakamega (S)	Alupe	Kibos	Kiboko	Kakamega (L)	Kakamega (S)
Parents	7	24.32**	16.06**	72.50**	117.21**	47.30**	106.27**	24.20**
Heterosis†	22	7.76	4.29**	35.13**	27.97**	29.05**	30.01**	31.80**
h	1	98.71**	48.94**	401.55**	263.77**	469.87**	119.01**	475.65**
h	7	1.49	2.73	38.48**	36.74**	17.66*	42.51**	21.61**
s	14	4.39	1.88	7.28	6.74	3.26	17.40*	5.19*
Deviations	24	4.24	1.14	5.11	4.32	6.76	7.09	2.34
Error	106	6.66	5.00	11.34	13.06	12.95	9.27	13.45

*, ** significant at the .05 and .01 probability levels, respectively.

† h = average heterosis of the single crosses; h = specific heterosis of a line; s = specific heterosis in a single cross.

L and S in parenthesis indicate long rainy season and short rainy season at the same site.

Table 39. Mean squares for genetic effects (fixed model) of agronomic characters in sorghum all sites combined in Kenya during 1992.

Source	df	Grain yield	Threshing percent	df	1000-seed weight	Days to 50% anthesis	df	Plant height	Panicle length	Panicle exsertion
		kg ha^{-1}†	%		g	d		cm	cm	cm
Parents	7	472.32**	76.93**	7	13.33**	35.25**	7	2479.52**	23.09**	49.55**
Heterosis‡	22	144.07*	20.21**	22	4.40**	8.02**	22	870.47**	5.31**	25.31**
h	1	2216.32**	151.17**	1	69.92**	127.39**	1	12756.69**	89.87**	328.88**
h	7	30.48	31.06**	7	0.93	3.09	7	623.94**	0.56	25.64**
s	14	52.84	5.42	14	1.45	1.97	14	144.71**	1.65*	3.46*
Deviations	24	73.44**	5.82	24	1.38	1.39	24	41.82	0.72	1.26
Entries X Env	159	168.44**	35.96**	106	5.95**	4.41**	212	213.66**	2.42**	8.99**
Error	424	15.37	11.81	318	3.55	2.23	530	53.85	1.74	4.01

*, ** significant at the .05 and .01 probability levels, respectively.

† multiply mean squares for grain yield by 10^4.

‡ h = average heterosis of the single crosses; h = specific heterosis of a line; s = specific heterosis in a single cross.

an analysis with minimum confounding of genetic effects was possible and provided detailed information. According to the model used (Gardner and Eberhart, 1966), a parental effect contains an additive and a dominant effect measuring the inbreeding depression in a partly inbred parent. Since sorghum is a highly inbred plant, the parents used are considered homozygous and therefore the parental effects were exclusively additive. Most loci contributing to the traits of interest should have been fixed. Accordingly, and for all practical purposes, variation due to parental effects should be considered as variation of additive effects. Overall heterosis was attributed to dominance effects, whereas deviations from the full model provided information for the absence, or presence, of significant epistatic effects. Otherwise epistatic effects could not be tested statistically in the analysis. The different line and single cross genetic effects for individual locations and for the overall locations are provided in Appendix C, Tables C1 to C12

The present results indicated that variations in the mean grain yield among the cultivars studied were attributable largely to additive and dominance effects. The close similarities that had earlier been indicated between the mean grain yields of fertile single crosses and three-way crosses can also be considered indications of epistasis not being an important factor in the expression of yield in the particular hybrids. The effects of epistasis in the expression of yield can not, however, be considered negligible since significant deviations were indicated at two of the four locations. These findings support some of the earlier reports in the literature that indicated both additive and dominance to be of importance in the expression of grain yield in sorghum, with the additive gene action being more important (Bittinger et al., 1981; Finkner et al., 1981; Malm, 1968; Patanothai and Atkins, 1974). Liang and Walter (1968) found dominance and additive X additive, and dominance X dominance epistatic gene effects important and stated that epistasis could not be considered negligible. However, Ross (1969) and Patanothai and Atkins (1974b) reported epistasis as being unimportant in the expression of yield.

Additive and dominance effects were important for the expression of threshing percentage while epistatic effects being negligible. Similarly, for 1000-seed weight, days to 50% anthesis, plant height, panicle length, and panicle exsertion additive and dominance effects were equally important. In all these traits the deviations from the full model were not significant, an indication of the small importance epistasis has in the expression of these traits in the hybrids. The importance of both additive and dominance effects for seed weight in sorghum has been reported in the available literature (Beil and Atkins, 1967; Fanous et al., 1971; Jan-Orn et al., 1976; Lamb et al., 1987; Lothrop et al., 1985b; Voigt et al., 1966).

Prediction of Three-way Cross Grain Yield for Trials in Kenya

The observed and predicted mean grain yield of the three-way cross hybrids at each of the locations and for the overall means in Kenya during 1992/93, and their correlation coefficients are presented in Appendix, Tables D2 to D6. Non significant correlations were indicated in all the five methods at Kiboko (Table D3) and in Kakamega during the short rainy season (Table D5). The results from the predictions of grain yield at Kibos (Table D4), Kakamega during the long rainy season (Table D4) and overall locations (Table D6) indicated significant correlations between the observed and predicted mean grain yields using all the five methods. From the components of heterosis in the genetic analysis only average heterosis was significant at the locations; consequently, Method 1 was based only on the additive and average heterosis effects. By including only the significant genetic effects of a particular set of lines, Method 1, theoretically, is expected to provide superior predictions. The magnitude of its superiority over the other methods, however, should be appreciable before the method is fully applied. The line specific heterosis and single cross specific heterosis of the genetic analysis are included in the general and specific effects, respectively, of the factorial designs used in Methods 2 and 3.

The parents used in this study were selected lines for their general combining abilities. This can be seen from the genetic effects in Appendix C (Tables C1 to C12) where the additive effects indicated higher frequencies of statistical significance while the specific line and specific cross heterosis were less frequent in significance. Therefore, grain yield of the non-parental single crosses ($A_i * R_j$) would be determined mainly by the general combining ability of the parents. Similar results have been reported in studies with highly selected maize lines (Otsuka et al., 1972). However, when unselected lines are used and experimental errors are kept low, Method 2 should give better predictive results than Method 3.

Because of the simplicity in using Method 2 (Jenkins, 1934, Method B) and further backing from extensive information drawn from similar studies in maize (Otsuka et al., 1972, Stuber et al., 1973), in sorghum (Patanothai and Atkins, 1974), and in other crops (Jha and Khehra, 1988; Skaracis and Smith, 1984) the use of the non-parental single crosses seems adequate for predicting grain yield of three-way cross hybrids of sorghum. This approach is also practical, because A-line * R-line crosses are a necessary step taken in all breeding programs to determine general and specific combining abilities. Otsuka et al. (1972) have shown efficiency of predictions to increase as an increasing number of environments are included because the contribution of both cultivar by environment interaction, and experimental error to the phenotypic variance of the mean for a hybrid is reduced as the number of environments increases. Experimentation with a wider range of cultivars and environments probably, therefore would provide more conclusive information.

CHAPTER V
SUMMARY AND CONCLUSIONS

Three groups of trials were conducted between 1990 and 1993 in Texas, and in Kenya. The first group consisted of three different sets of experiments at College Station in 1990, for preliminary evaluation of single, three-way, and double cross sorghum hybrids. In 1991 and 1992 replicated trials were conducted, using selected entries from preliminary evaluations, at College Station, Halfway, Corpus Christi, and Chillicothe. Entries for these replicated trials included parental lines, single crosses, three-way crosses, and double crosses. Parental sterile lines of A_1 and A_2 cytoplasms were utilized. Objectives for trials in Texas were primarily to evaluate performance of the different hybrid-types of sorghum, analyze their respective environmental stability and evaluate prediction of the three-way crosses using Jenkins' Method B, and secondarily to assess within-hybrid variability and heterosis in single crosses and three-way crosses. The last group of trials were conducted in Kenya during 1992/93 at four locations (Kibos, Kiboko, Kakamega and Alupe) with two season crops at Kakamega. Entries for trials in Kenya were a complete set, excluding reciprocals, of parental lines (B- and R-lines), sterile single crosses, fertile single crosses, and three-way crosses. Objectives for experiments in Kenya were similar to those for Texas trials except that different types of gene effects involved in the expression of the characters studied also were estimated.

Characters measured varied across experiments and locations, and included grain yield, threshing percentage, test weight, 1000-seed weight, days to 50% anthesis, plant height, panicle length, and panicle exsertion. In preliminary trials at College Station in 1990, a single cross was the highest yielding in all the three different sets. Hybrid types uniformly outperformed parental lines, and single crosses outperformed three-way crosses and double crosses in two of the three trials. Hybrid types were higher yielding, earlier in days to 50% anthesis, had higher test weight, and were taller in height. Performance of A_2Tx632*RTx430, a partially male-sterile F_1 hybrid, was competitive in performance with those of fertile single crosses.

In Texas trials of 1991 and 1992, a single cross was highest yielding in five of the eight environments, a three-way cross in two, and a double cross in only one of the environments. Two single crosses, ATx631*SC103-12E and A_2Tx632*SC103-12E, each ranked highest in grain yield in two different environments. Hybrid types uniformly outperformed inbred lines for all characters studied. Among different hybrid types, significant differences for the characters studied were less frequent between single and three-way crosses as compared to differences between single crosses and double crosses, and between three-way crosses and double crosses. The conventional combined analysis of variance indicated significant differences for environments and entries sources of variation, and for entries X environments interactions. Occurrence of significant entries X environments interactions permitted evaluation of cultivars for stability of performance across different environments. Hybrids outperformed parental lines in all characters studied. Single crosses significantly outyielded three-way and double cross hybrids. Double crosses had significantly higher 1000-seed weight than single and three-way crosses, while three-way crosses were the tallest, though not significantly different from the single crosses, which had significantly longer panicles than the other two hybrids. Three-way crosses and single crosses were similar in panicle exsertion which was higher than that of double crosses.

Stability analysis of the Texas trials indicated highly significant mean squares for environments (linear) in all characters. Significant entries X environments (linear) mean squares was indicated only for panicle length, indicating that the cultivars responded differently to the various environments for panicle length. Hybrids differed from parental lines in their response to environments for grain yield, 1000-seed weight, plant height, and panicle exsertion as evidenced by significant differences in slopes [P vs H X Env(l)]. The hybrid types did not differ from each other for all characters in their responses to environments. Pooled deviation mean squares for all characters except panicle exsertion were significant, indicating that a high degree of nonlinearity existed in the entry/environment relationship. Deviations from regression for parental lines were highly significant for all characters, while those for single crosses were significant for all the characters except panicle length. The deviations from regression for three-way crosses were not significant for panicle length and panicle exsertion. Double cross deviations from regression were not significant for grain yield and panicle exsertion. Generally, double crosses had lower deviation mean squares for most of the characters followed by three-way crosses, and single crosses; whereas parental lines had larger deviations. This was evidence of stability increasing from the parental lines to the single crosses, three-way crosses, and finally double crosses as the most stable type.

On the arithmetic scale most of the low yielding sorghum entries indicated small S^2_{di} values. This should be considered an artifact of scaling. Because parental lines yielded so much less than hybrids, they could not be compared for this parameter. The low yielding entries might be constrained by the additive nature of the model on the arithmetic scale. A transformation of grain yield data was performed to $\log_{10}$ resulting in significant changes in deviation mean squares. Parental lines now indicated highly significant deviation mean squares, whereas single crosses' deviation mean squares were significant at the 0.05 level of probability. Three-way crosses and double crosses deviation mean squares were not significant. For special mention among the three-way crosses is the cross (A_2Tx632*BTx630)*SC103-12E, which performed well across environments, had a high mean yield overall environments , b_i = 1.03, and a mean square deviation close to zero.

Within-plot variability for plant height, panicle length, and panicle exsertion for the different types was evaluated using their respective standard deviations. The variation in plant height at the individual locations and combined over locations indicated that differences were minimal to be of agronomic importance, though the limits that might be tolerated would differ among sorghum growers. Also, these standard deviations were not tested statistically for significance. Variability within a three-way cross might result either from differences between parents of the male-sterile single cross or from heterogeneity within the parental lines. If the predominant cause of high variability in a hybrid was a pronounced difference between parents of the sterile single cross, then three-way hybrids showing excessive variability might be avoided by not using diverse parents in the sterile single cross.

High-parent heterosis (heterobeltiosis) of single and three-way crosses ranged from -44.8 to 207.9% in Texas trials of 1991 and 1992. Single crosses exhibited higher heterosis than did three-way hybrids. Negative heterotic values were preponderant in the three-way crosses involving a male-sterile female and a male-fertile F_1 as the pollen parent. The most appropriate three-way cross for commercial production should have a male-sterile F_1 and a fertility-restoring line as parents. Crosses involving SC103-12E exhibited high heterotic values in single crosses.

Prediction of three-way cross mean grain yields using Jenkins' Method B indicated highly significant correlation with the observed grain yield means at two of the eight locations. These results when compared with others previously reported, especially in maize, indicate that the nonparental single crosses can be appropriately used in the prediction of three-way cross performances in sorghum.

In the trials in Kenya during 1992/93, mean yield of three-way crosses was significantly higher than for fertile single crosses in one of the environments, and slightly higher, and lower in the other two environments. Three-way crosses outyielded single crosses in the better environments, Kibos and Kakamega (short rainy season). A fertile single cross was the highest yielding in two environments, and a three-way cross and a sterile single cross in one of each of the other environments. Fertile single crosses and three-way hybrids had equivalent performances for all the other components of yield and agronomic characters studied. These hybrids outperformed sterile single crosses in all characters except 1000-seed weight and panicle length, which were not significantly different in the combined analysis. Sterile single crosses were superior to parental lines in all characters except threshing percentage, in which nonsignificant differences were indicated.

The data for grain yield were analyzed for stability using both the arithmetic scale and the logarithmic scale. The analysis of variance on the combined data when stability parameters were estimated showed that a large proportion of the total entries X environments variation was attributable to differences between environments (linear) and differences among the fitted regression lines. Entries X environments (linear) mean squares were not significant for grain yield on the arithmetic scale, but were significant on the logarithmic scale. Significance for entries X environments (linear) was indicated for all the other characters except 1000-seed weight. Significant pooled deviations mean squares were indicated for all the characters except grain yield on the logarithmic scale. Fertile single crosses had the largest deviation mean squares for grain yield on both the arithmetic and logarithmic scales. Three-way crosses and sterile single crosses had nonsignificant deviation mean squares for grain yield on the logarithmic scale. Three-way crosses also had the smallest and nonsignificant deviation mean squares for threshing percentage, an important component of grain yield. The regression coefficient for three-way crosses was greater than 1.0, indicating their responsiveness to improving environments; coupled with their above average mean grain yield and mean threshing percentage overall environments, three-way crosses were considered most stable under conditions of this study. Three-way crosses also showed stability for days to 50% anthesis and panicle length. Fertile single crosses were unstable for grain yield on both the scales, with significant S^2_{di}.

Within-plot variabilities were found to be high in the parents compared to the hybrids, especially for plant height. The variabilities in single crosses and three-way crosses were nearly similar in most instances. The problem of excessive variability in Kenya might not be as important a desirability factor as is the case for Texas since harvesting of sorghum in the latter case is by combine harvesters while in the former it is done by hand. Stability of performance is a more important consideration than is the expected variability in three-way crosses, which also can be controlled by selection of parents to be used in the production of the sterile single crosses.

Heterosis for grain yield ranged from -61.1 to 450.5%. Large entries X environments interaction resulted in heterotic values from all locations combined to indicate nonsignificance. Higher heterosis was observed at Kiboko. High-parent heterosis was noted in sterile single crosses, with ATx635*BTx3197 and ATx3197*BTx631 indicating significant and positive heterotic values. High parent heterosis in sterile single crosses is of great advantage to seed producers in reducing production costs of three-way hybrid seeds, and eventually in the final seed cost to farmers. Three-way hybrids showed less heterosis than fertile single crosses, as expected on genetic grounds.

Conventional and genetic analyses in the present study provided information on the type of genetic effects present in a fixed set of cultivars. Significant average heterosis found in single crosses indicated the importance of nonadditive genetic effects for all the traits. Overall heterosis was not significant for grain yield at all environments except Kiboko and in the combined analysis, indicating the importance of additive gene effects for the variations in mean grain yield. The close similarities that had been indicated between mean grain yields of fertile single crosses and three-way crosses can be considered an indication of non-importance of epistasis in the expression of yield. The effects of epistasis on yield cannot, however, be considered negligible, since significant deviations from the full model were indicated at two locations. Additive and dominance effects were important for the expression of threshing percentage, 1000-seed weight, days to 50% anthesis, plant height, panicle length, and panicle exsertion. In all these traits the deviations from the full model were not significant, indicating the non-importance of epistasis in their expression.

The five prediction procedures employed indicated significant correlations with observed grain yield at Kibos and at Kakamega (long rainy season), and in the overall environments combined. However, all the methods resulted in nonsignificant correlations at Kiboko and the short rainy season at Kakamega. This study demonstrates that a quantitative genetic model can be used successfully to predict the means of three-way crosses. However, because of the simplicity in using Jenkins' Method B, and placing credence on extensive information from similar studies in maize, sorghum, and other crops the use of the nonparental single crosses seems adequate for predicting grain yield in three-way cross hybrids of sorghum.

If three-way cross hybrids are desirable, the current practice of isolating lines and preliminary testing of their combining abilities followed by predicting the three-way cross of the selected single crosses can be appropriate. The fertile single crosses should be tested in preliminary experiments at several environments with minimum replications, and the three-way crosses can be predicted from the mean of the two non-parental single crosses involved in each three-way cross. Sequential testing eliminates the poorer entries until the best performing hybrids are identified. A reduced number of three-way cross hybrids could then be produced for evaluation over a large range of environments to provide superior candidates of commercial release. Genetic combining ability should also be considered in the A- X B-line crosses for male-sterile F_1 seed parents just as in A- X R-line crosses for F_1 hybrids. With proper selection of A- and B-lines, it should be possible to create male-sterile F_1 female parents that would produce high yields of three-way cross hybrid seed be agronomically acceptable as seed parents, and impart acceptable variability and superior performance to their three-way crosses for farmers' use.

The F_1 male-sterile parents were earlier maturing which should allow earlier harvest of the hybrid seed and reduce grain drying costs. The production of a male-sterile F_1 requires little more effort than the maintenance of an A-line, and both can be done in the same isolation block. The reduced seed production costs due to increased yields of the male-sterile single cross should benefit the farmer. Three-way hybrids introduce variability to the cultivated population. From the evidence of this study, three-way crosses combine greater stability with substantial performance.

Three-way cross hybrids also might provide an opportunity for sorghum breeders to adjust the genetic composition of cultivars rapidly by substituting component inbred lines. The cultivars could, thereby, respond to local conditions such as sudden changes in pathogen virulence.

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APPENDIX A

RANGES AND WITHIN-TYPE VARIATIONS

Table A1. Ranges and within-plot standard deviations in the different types for plant height, panicle length, and panicle exsertion in subset 1, subset 2, and main set at College Station in 1990.

	Plant height			Panicle length			Panicle exsertion		
	Subset 1	Subset 2	Main set	Subset 1	Subset 2	Main set	Subset 1	Subset 2	Mainset
Parents									
Range (cm)	86-127	85-118	59-160	14.3-29.4	10.5-30.0	17.0-34.0	1.7-15.6	0.0-19.7	-1.0-20.0
Std. dev.	11.2	8.1	16.6	4.0	5.5	5.8	4.4	4.0	6.1
Single-crosses									
Range (cm)	101-161	93-152	82-172	17.9-34.9	17.7-34.0	22.0-34.2	4.6-23.1	3.3-22.3	4.1-21.6
Std. dev.	7.8	13.2	15.3	4.8	4.5	4.1	5.0	5.8	6.3
Three-way crosses									
Range (cm)	102-178	77-158	62-192	15.6-37.5	12.8-37.0	12.0-40.0	1.8-26.0	0.0-21.5	4.6-22.3
Std. dev.	15.4	17.5	20.7	4.8	5.1	5.43	5.3	5.8	6.7
Double crosses									
Range (cm)	102-184	83-174	65-190	15.3-36.9	13.3-38.0	14.0-39.0	0.3-27.2	0.0-25.5	4.2-23.7
Std. dev.	18.1	17.6	22.2	4.6	5.1	5.32	6.7	6.4	7.0

Table A2. Ranges and within-plot standard deviations for plant height, panicle length, and panicle exsertion in parents, single, three-way, and double cross hybrids of sorghum from 1991 and 1992 experiments at four locations in Texas.

			1991			1992
Location†	Type‡	Parameter	Plant height	Panicle length	Panicle exsertion	Plant height
Cstn	Parents	Range (cm)	77-147	18.4-33.2	-4.3-21.6	89-141
		Std. dev.	19.7	4.3	7.3	16.0
	SC	Range (cm)	112-163	23.8-32.8	7.2-29.4	103-172
		Std. dev.	12.0	2.3	5.2	16.7
	TWC	Range (cm)	111.7-159.6	22.3-32.2	14.3-26.8	88-173
		Std. dev.	10.0	2.0	3.2	16.3
	DC	Range (cm)	116-164	21.1-29.2	11.9-25.7	114-175
		Std. dev.	12.0	1.8	2.8	15.4
Halfway	Parents	Range (cm)	94-147	20.0-34.2	-2.3-19.8	90-156
		Std. dev.	15.4	3.6	5.6	18.4
	SC	Range (cm)	125-188	21.2-38.2	-3.8-26.4	89-159
		Std. dev.	14.5	2.9	5.3	13.4
	TWC	Range (cm)	129-176	26.0-33.9	9.4-22.9	103-160
		Std. dev.	11.5	2.0	3.4	12.6
	DC	Range (cm)	131-175	25.5-33.3	8.6-20.1	86-172
		Std. dev.	12.0	1.8	2.6	14.6
Corpus	Parents	Range (cm)	51-143	17.0-35.6	-4.5-18.2	80-152
		Std. dev.	25.9	4.2	5.8	21.1
	SC	Range (cm)	71-159	21.4-35.0	6.4-27.2	110-174
		Std. dev.	24.4	2.9	4.0	15.4
	TWC	Range (cm)	73-161	22.6-32.4	10.5-26.0	114-185
		Std. dev.	22.6	2.6	3.5	13.9
	DC	Range (cm)	76-142	21.7-33.0	9.4-20.5	118-171
		Std. dev.	19.6	2.9	2.9	14.7

Table A2. Continued.

Location†	Type‡	Parameter	1991 Plant height	1991 Panicle length	1991 Panicle exsertion	1992 Plant height
Chillicothe	Parents	Range (cm)	63-142	19.4-29.0	-3.0-22.0	79-150
		Std. dev.	19.8	8.5	5.9	16.4
	SC	Range (cm)	114-202	23.0-46.0	-0.5-21.0	108-154
		Std. dev.	16.3	4.0	5.8	10.3
	TWC	Range (cm)	120-193	22.0-32.7	4.3-21.5	110-172
		Std. dev.	15.4	2.8	4.2	10.5
	DC	Range (cm)	114-167	23.7-36.0	-3.3-16.3	113-152
		Std. dev.	15.4	3.0	4.7	10.5
Over all locations-years						
	Parents	Range (cm)	51-157	19.4-35.6	-4.5-22.0	
		Std. dev.	20.9	5.7	6.2	
	SC	Range (cm)	71-202	21.2-46.0	-3.8-29.4	
		Std. dev.	18.4	3.3	6.0	
	TWC	Range (cm)	73-193	22.0-33.9	4.3-26.8	
		Std. dev.	17.1	2.7	4.3	
	DC	Range (cm)	77-175	21.1-36.0	-3.3-25.7	
		Std. dev.	16.4	2.7	4.6	

† Col Stn : College Station, Corpus: Corpus Christi.

‡ SC, TWC, and DC: Single crosses, three-way crosses, and double crosses, respectively.

Table A3. Ranges and within-plot standard deviations for plant height, panicle length, and panicle exsertion in parents, sterile and fertile single crosses, and three-way hybrids of sorghum from 1992 experiments at five sites in Kenya.

			Character		
Site	Type	Parameter	Plant height	Panicle length	Panicle exsertion
Kibos	Parents	Range (cm)	94-172	14-40	-11-25
		Std. dev.	18.2	4.7	8.2
	Sterile single crosses	Range (cm)	122-202	20-40	-13-21
		Std. dev.	16.3	4.1	7.4
	Fertile single crosses	Range (cm)	119-292	15-41	-11-30
		Std. dev.	44.2	4.6	7.3
	Three-way crosses	Range (cm)	102-298	14-43	-12-38
		Std. dev.	42.7	3.9	8.3
Kiboko	Parents	Range (cm)	27-162	6-35	0-24
		Std. dev.	21.9	4.6	6.8
	Sterile single crosses	Range (cm)	79-197	18.5-38	0-24
		Std. dev.	18.2	4.3	6.0
	Fertile single crosses	Range (cm)	40-230	17.5-39	3-30
		Std. dev.	31.8	4.3	6.6
	Three-way crosses	Range (cm)	70-230	11.5-42	0-38
		Std. dev.	25.3	4.3	6.7
Kakamega (L)†	Parents	Range (cm)	83-176	9-34	-9-25
		Std. dev.	20.7	4.8	7.9
	Sterile single crosses	Range (cm)	98-185	7-37	-9-26
		Std. dev.	20.7	5.3	7.2
	Fertile single crosses	Range (cm)	104-326	13-41	-12-28
		Std. dev.	37.5	4.9	8.5
	Three-way crosses	Range (cm)	93-256	8-41	-12-29
		Std. dev.	34.7	5.1	7.2

Table A3. Continued.

			Character		
Site	Type	Parameter	Plant height	Panicle length	Panicle exsertion
Kakamega (S)†	Parents	Range (cm)	95-164	5-35	-9-33
		Std. dev.	15.7	4.9	7.2
	Sterile single crosses	Range (cm)	110-210	15-41	-3-31
		Std. dev.	25.3	4.3	7.1
	Fertile single crosses	Range (cm)	119-225	13-35	-5-32
		Std. dev.	22.3	3.5	6.6
	Three-way crosses	Range (cm)	94-242	10-45	-9-39
		Std. dev.	26.0	4.3	6.7
Alupe	Parents	Range (cm)	63-154	4-32	-9-30
		Std. dev.	16.5	4.3	9.0
	Sterile single crosses	Range (cm)	100-236	16-40	-1-35
		Std. dev.	28.0	4.2	6.8
	Fertile single crosses	Range (cm)	111-242	15-45	-4-34
		Std. dev.	27.6	4.6	7.0
	Three-way crosses	Range (cm)	104-250	15-44	-11-37
		Std. dev.	26.6	4.6	8.2
Over all sites	Parents	Range (cm)	27-176	4-40	-11-33
		Std. dev.	19.9	5.0	8.2
	Sterile single crosses	Range (cm)	79-236	7-41	-13-35
		Std. dev.	22.9	4.8	8.0
	Fertile single crosses	Range (cm)	40-326	13-45	-12-34
		Std. dev.	34.8	4.7	8.0
	Three-way crosses	Range (cm)	70-298	4.75	-12-39
		Std. dev.	34.3	8-5	8.3

† Kakamega (L) and Kakamega (S) stand for the long and short rainy seasons at Kakamega, respectively.

APPENDIX B
HIGH PARENT HETEROSIS

Table B1. Percentages of high-parent heterosis (%) for grain yield of sorghum single, and three-way crosses in 1991 and 1992 at four locations in Texas.

	1991				1992				Over all
Entry†	CStn‡	Hway	Corp	Chill	CStn	Hway	Corp	Chill	Texas
Single crosses									
1*2	20.4	12.4	27.2	15.3	-29.3	-5.6	8.2	51.4	17.1
1*3	67.2	69.5**	50.1*	74.0	88.6	53.7	106.4*	58.0	87.1*
1*4	6.2	29.8	70.6*	42.6	106.2	20.6	51.1	63.6	42.0
1*6	61.8	34.8	33.1	109.1**	-28.2	52.5	48.5	74.3*	48.1
1*7	12.4	41.6	77.6**	139.0**	39.8	64.9	125.2**	89.6**	78.1*
1*8	109.8*	53.2*	72.7**	72.5*	61.0	93.4*	136.4**	95.8*	95.4**
2*3	44.5	31.8	47.9	32.6	73.9	47.4*	70.2	72.9*	74.1*
2*4	35.6	32.4	39.0	32.3	43.3	34.2	24.0	78.6*	45.9
2*5	121.0*	31.1	135.4**	18.6	15.6	70.5	316.6*	77.8*	69.4
2*6	90.4	26.1	24.4	89.1**	76.9	77.1*	67.9	85.1*	70.8*
2*7	77.1	46.5*	65.4**	44.4	17.6	67.3*	135.3**	72.7*	85.0**
2*8	86.5	32.6	52.4	64.3*	92.2	97.1*	64.1	80.1*	84.9*
3*5	207.9*	96.0**	34.4	162.9**	108.2	85.6	119.0**	90.8*	97.0**
3*6	86.1	51.2	32.5	134.5*	59.7	50.1	85.9*	47.2	59.3
3*7	19.7	107.5**	73.2**	169.2**	88.8	28.6	80.6*	95.7*	80.9*
3*8	52.5	82.6**	38.9	20.6	17.9	87.4	87.1*	83.4*	68.4*
4*6	43.6	29.9	13.3	37.6	28.0	87.1	41.2	47.4	39.0
4*7	38.9	54.3*	66.4**	46.7	108.6	15.2	48.5	76.4*	61.3*
4*8	75.7	31.4	36.4	48.4	89.3	38.3	50.8	81.2*	56.0*
Three-way crosses									
(3*1)*6	26.7	-7.7	-7.5	19.8	29.6	-7.7	-2.4	16.2	4.4
(3*1)*7	29.8	-9.4	12.0	33.2	1.9	-7.3	12.0	42.7*	10.4
(3*1)*8	22.0	-4.5	-11.6	4.8	-4.6	7.7	0.9	14.0	2.0
1*(4*6)	-44.4	-19.2	11.0	-13.5	5.8	13.3	-16.1	15.4	-2.5
1*(4*7)	-33.9	-1.6	-13.8	-6.7	-30.2	24.9	-0.9	-11.9	-10.8
1*(4*8)	-44.8	-5.4	11.5	-8.9	-14.5	-4.5	-9.5	-10.4	-10.7
2*(3*6)	-31.6	-2.6	-1.6	23.1	15.5	-6.2	-39.2	5.5	-4.8
2*(3*8)	-8.3	-8.6	-27.5	39.1	28.5	-19.2	-22.4	-3.2	-7.9
2*(3*7)	-22.6	-27.9	-17.2	8.3	-21.2	-10.4	6.0	-11.8	-14.7
2*(4*6)	-20.4	-3.3	9.6	21.2	10.3	-12.9	-12.2	31.7	1.4
3*(4*7)	-43.1	-1.1	-24.9	-18.9	-34.1	-14.4	-22.3	-18.4	-20.1
(2*1)*6	65.1	14.7	38.3	56.2	73.9	53.0	69.5	7.1	60.1*
(2*1)*8	117.2*	11.8	58.4*	43.2	13.9	73.8	128.9**	17.0	62.7*
(3*5)*7	30.0	-11.5	12.1	11.0	-25.7	-0.9	7.4	-2.2	-5.8
(3*5)*8	-26.7	-31.2	-4.4	2.8	-57.9	-31.7	-14.3	-16.4	-23.8

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

† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 B_2Tx632, 4 B_2Tx636, 5 RTx432, 7 SC103-12E.

‡ Locations: CStn- College Station, Hway- Halfway, Corp- Corpus Christi, and Chill- Chillicothe.

Table B2. Percentages of high-parent heterosis (%) for grain yield of sorghum single and three-way crosses in 1992/93 at four locations in Kenya.

Entry†	Kibos	Kiboko	kakamega (L)‡	Kakamega (S)	Kenya
Sterile single crosses					
2*1	22.6	-28.5	61.8	-0.6	44.4
3*1	68.2	5.0	-6.6	160.9*	51.3**
3*2	161.5**	120.0*	-35.3**	18.7	45.8*
4*3	110.1*	200.0**	-4.5	218.8**	105.6**
4*1	390.9**	49.9	-68.3**	145.9*	87.5
4*2	40.1	162.4*	-30.1*	269.5**	106.3
Fertile single crosses					
1*5	-4.9	-45.5**	-19.3*	-23.6	-22.4
1*6	58.8**	33.4	-61.7**	58.3	27.3
1*7	222.9**	450.5**	104.3**	-44.9	188.4
1*8	110.8**	625.7**	76.1**	166.7**	165.2
2*5	25.3	-24.2	38.0**	62.4**	28.3
2*6	30.3	59.5*	-64.1**	2.8	9.7
2*7	-162.3**	371.3**	-48.0*	360.7	204.6
2*8	-21.2	342.7**	-29.3	25.8	53.1
3*5	29.7*	12.1	56.5**	26.4	30.7
3*6	-75.3**	-19.0	-16.3	-71.4	-44.6
3*7	32.8	140.1**	-19.2	298.6**	91.9
3*8	132.1**	50.1	-38.8**	-65.7	8.2
4*5	31.1*	60.6**	3.8	87.6**	48.4
4*6	-73.5**	66.7**	-17.0	148.2**	28.9
4*7	199.7**	62.4	-21.3	344.8**	155.3
4*8	168.6**	212.5**	-31.1	-56.8	84.1

Table B2. Continued.

Entry†	Kibos	Kiboko	kakamega (L)	Kakamega (S)	Kenya
Three-way crosses					
(2*1)*5	6.3	-21.2	-4.2	-25.3	-11.1
(2*1)*6	-45.1*	57.2*	0.9	-22.3	-6.2
(2*1)*7	253.9**	299.6**	18.1	19.1	117.2
(2*1)*8	31.1	439.6**	51.6*	205.7**	147.6
(3*1)*5	36.9*	-12.1	22.3**	-25.7	4.5
(3*1)*6	80.1**	33.4	-31.9**	64.3**	63.4
(3*1)*7	23.6	404.6**	-58.8**	88.6**	71.7
(3*1)*8	63.8*	185.6**	-36.6**	-20.9	18.9
(4*1)*5	47.2**	-24.4	45.1**	-2.1	16.5
(4*1)*6	105.5**	42.9	-49.9**	14.3	44.9
(4*1)*7	29.8	200.1**	-33.0	7.2	48.2
(4*1)*8	85.5**	116.7**	-13.7	-42.1	34.0
(3*2)*5	56.7**	-9.1	-7.8	-33.6	1.6
(3*2)*6	30.0	22.8	-29.6*	276.5**	68.1
(3*2)*7	20.8	59.1*	95.1**	125.4*	62.5
(3*2)*8	-26.3	45.5	-18.2	50.3	6.7
(4*2)*5	-1.4	36.4*	20.6*	3.7	13.1
(4*2)*6	53.6*	66.7**	-54.2**	84.6**	64.2
(4*2)*7	225.0**	9.6	-15.5	-43.2	17.7
(4*2)*8	157.2**	81.0**	38.5*	54.9*	77.4
(4*3)*5	26.2	-12.1	19.3*	-25.1	2.4
(4*3)*6	66.6**	-18.3	-41.4**	2.5	4.6
(4*3)*7	55.5**	-30.0	-40.1**	-61.1**	-23.5
(4*3)*8	58.4**	16.7	-3.8	-28.5	6.2

*, ** Significant at 0.05 and 0.01 probability levels, respectively.
† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.
‡ Locations : Kakamega (S) and Kakamega (L) stand for Kakamega during long and short rainy seasons, respectively.

APPENDIX C

GENETIC EFFECTS IN SORGHUM

Table C1. Additive effects (a) and average line heterosis effects (h) for agronomic characters in sorghum at Kibos in 1992.

Cultivar	Grain yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h	a	h	a	h	a	h	a	h
BTx630	-1165.7**	-378.1	-10.8**	1.5	-1.2	1.4*	3.5**	1.5	12.5**	-19.0**	1.7**	0.7	2.4*	-5.7**
BTx631	-671.3**	-1010.3**	-6.7**	-2.9	-0.8	-1.1	5.8**	1.7	11.7**	-21.6**	5.2**	-0.1	-2.1	-4.7**
BTx3197	-151.3	-377.1	3.4*	-4.6**	0.2	0.0	-3.5**	2.0	-6.9*	-19.3**	-4.7**	-0.6	2.4*	0.4
BTx635	-1467.9**	116.6	-0.3	-2.0	-4.2	0.6	3.5**	2.8**	2.0	-13.0**	-2.9**	2.7**	2.0	-4.6**
Serena	2795.4**	804.6**	4.0**	1.5	1.2	2.4**	1.5	-5.0**	22.0**	70.2**	-2.1**	0.8	-8.5**	4.4**
Lulu D	1352.1**	-171.8	-1.7	2.1	-1.8	0.4	2.2*	-1.4	-1.6	0.2	-1.0	-1.3*	-9.8**	5.7**
RTx432	-540.1*	743.1**	8.6**	0.6	8.2**	-3.6**	-4.5**	-1.9	-19.4**	5.1	-0.9	-0.3	2.8*	2.5*
SC599-11E	-151.3	272.9	3.4	3.9	-1.5	-0.1	-8.5**	0.5	-20.2**	-2.6	4.6**	-0.3	10.8**	1.9

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C2. Specific heterosis effects in single crosses (h) of sorghum for agronomic characters at Kibos in 1992.

Cultivar	Grain yield	Threshing percent	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	-712.0	2.0	1.9	1.2	-9.2	0.1	0.6
ATx3197*BTx630	-240.0	-1.9	1.6	2.0	0.7	-1.4	-2.2
ATx3197*BTx631	1635.3*	8.8*	1.3	-3.1	-3.2	-1.5	3.0
ATx635*BTx3197	86.8	-1.0	0.9	1.7	-5.1	1.3	-3.6
ATx635*BTx630	96.2	-2.6	-1.9	-2.0	19.0*	-0.6	4.5
ATx635*BTx631	-866.7	-5.4	-3.8*	0.3	-2.1	2.0	-2.3
ATx630*Serena	-572.9	-1.8	-0.8	3.0	-4.1	0.4	0.3
ATx630*Lulu D	1286.0	5.6	0.3	-1.6	8.4	0.5	-0.1
ATx630*RTx432	3.6	2.0	-1.1	-1.1	-12.9	0.2	-0.8
ATx630*SC599-11E	138.8	-3.5	-0.2	-1.5	-1.8	0.8	-2.3
ATx631*Serena	291.7	1.7	-0.2	-0.8	12.6	-1.2	0.9
ATx631*Lulu D	495.4	-1.9	1.7	-2.5	11.1	2.6	1.3
ATx631*RTx432	874.8	-2.4	-0.6	0.5	-4.5	-0.8	-2.3
ATx631*SC599-11E	-1718.5**	-2.9	-0.3	4.3	-4.7	-1.2	-1.3
ATx3197*Serena	399.9	-0.7	0.6	-1.4	6.2	2.5	-0.1
ATx3197*Lulu D	-1010.8	-4.9	-2.4	5.0	-1.9	0.2	-0.9
ATx3197*RTx432	-1062.8	-1.8	0.1	-2.5	7.4	-0.2	1.7
ATx3197*SC599-11E	191.2	1.5	-2.9	-1.6	-4.1	-1.0	2.0
ATx635*Serena	-118.7	0.8	0.4	-0.9	-14.8*	-1.8	-1.1
ATx635*Lulu D	-770.6	1.2	0.4	-0.9	-17.6*	-3.3*	-0.3
ATx635*RTx432	184.4	2.1	1.5	3.1	10.0	0.9	1.3
ATx635*SC599-11E	1388.5*	4.9	2.5	-1.2	10.7	1.3	1.5

*, ** Significant at 0.05 and 0.01 probability level, respectively.

Table C3. Additive effects (a) and average line heterosis effects (h) for agronomic characters in sorghum at Kiboko in 1992.

Cultivar	Grain yield		Threshing percent		Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h	a	h	a	h
BTx630	-819.4**	-905.7**	-13.7**	0.4	5.4	-11.6	1.9	-0.9	0.3	-4.2**
BTx631	-486.1*	-328.6	5.7*	-7.3**	-20.0**	-10.3	-2.7*	3.5*	-8.2**	-0.2
BTx3197	-152.8	-575.5**	3.5	-4.5	13.7*	-23.1**	0.1	-0.8	3.4**	-3.4**
BTx635	-375.0	-84.7	3.5	-4.6*	1.6	-5.4	1.0	0.2	-5.1**	-0.4
Serena	2710.8**	-243.1	15.1*	-3.4	18.3**	12.2*	-3.8**	-0.2	1.3	3.1**
Lulu D	1069.4**	134.7	13.3**	-3.0	-10.0	6.2	-0.6	-1.1	-4.2**	4.2**
RTx432	-819.4**	956.9**	-19.3**	12.3**	-2.9	2.9	-0.2	-0.4	2.5*	1.7
SC599-11E	-819.4**	1045.8**	-8.2**	10.2**	-6.0	8.5	4.3**	-0.3	10.0**	-0.8

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C4. Specific heterosis effects in single crosses (h) of sorghum for agronomic characters at Kiboko in 1992.

Cultivar	Grain yield	Threshing percent	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	-824.1	-8.4	-13.9	-1.8	-2.0
ATx3197*BTx630	-132.7	-0.6	9.9	-0.1	-1.2
ATx3197*BTx631	401.2	-0.6*	-4.7	-0.6	3.1
ATx635*BTx3197	990.7	5.5	-6.0	0.7	-1.1
ATx635*BTx630	-345.7	1.3	3.5*	2.4	-0.1
ATx635*BTx631	-89.5	2.9	-0.8	-0.6	1.3
ATx630*Serena	-961.4	0.4	-12.0	1.1	-1.2
ATx630*Lulu D	668.2	3.8	4.9	-0.4	2.4
ATx630*RTx432	1094.1*	3.7	0.1	0.0	0.5
ATx630*SC599-11E	501.5	-0.2	7.6	-1.1	1.7
ATx631*Serena	-409.0	-0.1	9.4	-0.2	-0.4
ATx631*Lulu D	480.0	-1.8	8.0	2.3	-0.6
ATx631*RTx432	17.0	3.5	0.3	0.2	-0.1
ATx631*SC599-11E	424.4	4.4	1.8	0.7	-1.4
ATx3197*Serena	78.7	-2.3	0.0	1.2	-0.1
ATx3197*Lulu D	-1236.1*	-3.4	0.1	0.4	-0.2
ATx3197*RTx432	578.7	2.0	3.3	-0.8	0.1
ATx3197*SC599-11E	-680.6	-0.5	-14.6	-0.8	-0.7
ATx635*Serena	-1291.7*	2.0	2.6*	-2.1	1.7
ATx635*Lulu D	88.0	1.4	-13.0	-2.2	-1.6
ATx635*RTx432	-1689.8**	-9.3	-3.0	0.6	-0.5
ATx635*SC599-11E	-245.4	-3.7	5.3	1.2	0.4

*, ** Significant at 0.05 and 0.01 probability level, respectively.

Table C5. Additive effects (a) and average line heterosis effects (h) for agronomic characters in sorghum at Kakamega during the long rainy season in 1992.

Cultivar	Grain yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h	a	h	a	h	a	h	a	h
BTx630	-1096.9**	121.0	-16.8**	7.2**	1.9	-0.6	4.8**	0.3	12.3**	-10.9**	2.1**	-0.7	-3.3**	-2.7**
BTx631	-1021.4**	-29.8	-11.4**	1.9	-3.1**	1.4	6.8**	-1.2*	4.2	-21.4**	3.3**	-1.3	-3.7**	-5.8**
BTx3197	775.3**	-116.4	2.6	-0.0	3.5**	0.3	-0.5	0.6	0.6	-19.3**	-3.9**	0.0	5.7**	0.4
BTx635	367.5**	-603.7**	9.8**	-9.0**	-1.5	0.3	1.1*	1.1*	7.3*	-4.1	-1.5**	0.5	5.8**	-2.9**
Serena	1693.1**	1360.0**	17.3**	5.8**	5.2**	-0.5	-5.2**	-1.1*	26.9**	38.4**	-4.0**	0.7	-2.9**	4.0**
Lulu D	240.8*	-701.1**	3.3	-9.4**	-6.5**	1.9	-0.5	-0.6	-14.6**	10.4	0.4	-0.6	-10.2**	8.1**
RTx432	-349.2*	-48.3	-2.8	0.9	1.9	-0.9	-5.5**	1.6**	-21.5**	1.2	-0.7	1.1	0.2	-0.1
SC599-11E	-609.2**	18.2	-2.3	2.6	-1.5	-1.9	-0.9	0.1	-15.2**	5.5	4.3*	0.4	8.7**	-0.3

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C6. Specific heterosis effects in single crosses (h) of sorghum for agronomic characters at Kakamega during the long rainy season in 1992.

Cultivar	Grain yield	Threshing percent	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	121.1	5.5	4.3	0.1	-13.2	0.0	0.8
ATx3197*BTx630	350.5	7.8	0.4	0.7	2.3	-2.4	1.1
ATx3197*BTx631	-323.2	0.4	-2.4	0.2	-4.9	1.3	-4.5
ATx635*BTx3197	399.7	-4.6	1.2	-0.2	-0.1	0.6	-5.0*
ATx635*BTx630	-773.9**	-11.9*	-3.7	3.0*	7.5	3.1	-0.3
ATx635*BTx631	225.8	3.6	0.1	-3.8**	8.4	-2.6	8.0**
ATx630*Serena	-612.8	-2.3	-1.8	-0.9	1.1	-0.5	1.4
ATx630*Lulu D	-102.3	-1.2	2.3	-0.4	0.7	0.9	0.2
ATx630*RTx432	585.5	0.6	1.2	-1.5	-5.0	-0.1	-1.3
ATx630*SC599-11E	432.0	1.5	-2.7	-1.1	6.5	-1.1	-1.9
ATx631*Serena	230.2	2.9	1.1	-0.1	16.2	1.7	-1.8
ATx631*Lulu D	-120.4	-7.7	1.7	0.7	9.1	-1.9	2.5
ATx631*RTx432	-36.7	-0.5	-4.4	2.0	-1.3	0.9	-2.1
ATx631*SC599-11E	-96.9	-3.5	-0.5	0.8	-14.4	0.6	-2.9
ATx3197*Serena	174.4	-1.8	-0.6	0.5	-10.4	1.7	-0.5
ATx3197*Lulu D	80.9	2.9	-1.1	-0.6	10.8	0.1	3.2
ATx3197*RTx432	-153.2	-1.7	0.6	-0.7	13.0	-0.7	2.2
ATx3197*SC599-11E	-529.3	-2.2	1.7	0.1	-10.7	-0.7	2.7
ATx635*Serena	208.2	1.2	1.3	0.5	-7.0	-3.0	-0.1
ATx635*Lulu D	141.7	5.9	-3.0	0.2	-20.7*	0.9	-5.8*
ATx635*RTx432	-395.7	1.7	2.6	0.2	-6.8	-0.1	1.2
ATx635*SC599-11E	194.1	4.2	1.5	0.2	18.6*	1.1	2.1

*, ** Significant at 0.05 and 0.01 probability level, respectively.

Table C7. Additive effects (a) and average line heterosis effects (h) for agronomic characters in sorghum at Kakamega during the short rainy season in 1992/93.

Cultivar	Grain yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h	a	h	a	h	a	h	a	h
BTx630	-342.5	-791.1**	-4.9**	-1.4	2.7*	-1.6	0.8	2.2**	22.8**	-16.6**	0.9	0.8	1.8	-3.3**
BTx631	-1287.2**	-353.9	-2.8*	-1.9	-0.7	-0.6	5.1**	1.0	4.6*	-7.8**	1.8**	-0.2	1.3	-4.3**
BTx3197	-147.9	-110.8	1.8	-3.2**	1.3	-1.0	2.4**	-0.3	0.3	-14.3**	-2.7**	0.3	3.1**	-3.3**
BTx635	-749.9**	924.7**	1.5	-2.5*	-2.0	0.1	2.8**	0.5	-4.3	-5.0*	-1.6*	1.3	2.6*	-0.8
Serena	3209.5**	-177.3	5.4**	0.7	3.3**	-1.7	-6.3**	-0.3	12.6**	32.4**	-4.6**	0.9	-6.0**	3.4**
Lulu D	865.0*	519.8*	2.4*	1.1	-2.3*	1.2	1.8*	-2.4**	-12.8**	3.6	-0.2	-0.2	-7.6**	5.2**
RTx432	-1456.6**	607.4**	-1.2	2.8*	-3.7**	3.7**	-3.9**	-0.4	-13.8**	0.7	2.2**	-2.0	1.3	1.3
SC599-11E	-90.6	-618.9**	-2.3*	4.5**	1.3	-0.1	-2.6**	-0.3	-9.3**	-3.1	4.4	-0.9	3.6**	1.8

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C8. Specific heterosis effects in single crosses (h) of sorghum for agronomic characters at Kakamega during the short rainy season in 1992/93.

Cultivar	Grain yield	Threshing percent	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	-819.5	-1.3	-0.2	1.0	-22.8**	0.7	-1.1
ATx3197*BTx630	1255.5*	1.2	-1.1	-1.4	5.6	1.0	1.3
ATx3197*BTx631	-1081.8	0.6	-0.4	-1.4	-13.0*	-0.8	-1.9
ATx635*BTx3197	710.4	-0.4	0.3	-0.7	-8.1	0.9	-1.1
ATx635*BTx630	-208.4	-0.6	-1.6	1.4	4.3	0.6	-0.4
ATx635*BTx631	143.8	0.5	-0.2	1.0	33.9**	-2.4	3.3
ATx630*Serena	-1527.4**	-1.5	1.1	-0.2	2.9	0.3	-1.0
ATx630*Lulu D	-144.8	1.8	-2.8	-0.8	6.8	-0.4	0.6
ATx630*RTx432	-490.6	0.2	1.1	0.1	2.2	-1.3	-1.0
ATx630*SC599-11E	1935.2**	0.2	0.2	-0.2	1.1	-0.9	1.6
ATx631*Serena	1352.8*	0.4	-1.1	-0.8	5.2	0.6	-0.6
ATx631*Lulu D	44.2	-1.3	-0.1	0.6	6.5	1.0	2.6
ATx631*RTx432	-1169.0*	0.6	1.0	0.1	-3.7	0.0	-0.8
ATx631*SC599-11E	1529.6**	0.5	0.9	-0.6	-6.3	0.9	-1.5
ATx3197*Serena	-1080.1	0.3	1.3	0.9	6.7	0.2	1.5
ATx3197*Lulu D	-1013.9	-1.6	1.9	1.9	4.2	0.0	0.8
ATx3197*RTx432	2924.1**	0.3	-1.8	1.0	4.2	0.1	0.4
ATx3197*SC599-11E	-1714.3**	-0.4	0.1	1.6	0.3	-1.4	-0.9
ATx635*Serena	1254.7*	0.8	-1.3	0.1	-14.8*	-1.1	0.1
ATx635*Lulu D	1114.5	1.1	0.9	-1.7	-17.5**	-0.7	-3.9
ATx635*RTx432	-1264.5*	-1.0	-0.2	0.8	-2.7	1.2	1.4
ATx635*SC599-11E	-1750.5**	-0.4	-1.0	-0.9	4.9	1.4	0.7

*, ** Significant at 0.05 and 0.01 probability level, respectively.

Table C9. Additive effects (a) and average line heterosis effects (h) for plant height, panicle length, and panicle exsertion in sorghum at Alupe in 1992.

Cultivar	Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h
BTx630	15.5**	-20.6**	-0.0	0.5	4.1**	-4.8**
BTx631	6.6*	0.8	3.9**	0.1	4.4**	-6.0**
BTx3197	0.9	-17.2**	-2.6**	-0.3	4.2**	-2.6*
B.VG1	-0.3	0.1	-0.2	0.2	-4.8**	0.1
Serena	18.5**	28.0**	-2.0**	-0.4	-8.4**	4.6**
Lulu D	-14.7**	8.3**	-0.4	-0.4	-12.4**	6.2**
RTx432	-16.5**	2.9	-2.3**	-0.1	3.0**	2.8**
SC599-11E	-10.1**	-2.3	3.5**	0.3	10.0**	-0.2

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C10. Specific heterosis effects in single crosses (h) of sorghum for plant height, panicle length, and panicle exsertion at Alupe in 1992.

Cultivar	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	-9.9	-0.7	-0.1
ATx3197*BTx630	6.6	-0.6	2.9
ATx3197*BTx631	-16.7*	0.3	-1.7
ATx635*BTx3197	-16.0*	-0.5	-4.2
ATx635*BTx630	4.1	1.3	-2.6
ATx635*BTx631	31.9**	0.2	5.6*
ATx630*Serena	-28.8**	-1.3	-0.2
ATx630*Lulu D	10.2	0.8	-0.3
ATx630*RTx432	8.8	0.3	-0.9
ATx630*SC599-11E	9.0	0.2	1.1
ATx631*Serena	16.1*	0.2	-2.1
ATx631*Lulu D	5.1	0.9	1.4
ATx631*RTx432	-14.1	-1.5	-0.5
ATx631*SC599-11E	-12.4	0.6	-2.7
ATx3197*Serena	13.8	2.1	0.6
ATx3197*Lulu D	5.8	0.5	0.4
ATx3197*RTx432	8.7	0.3	0.4
ATx3197*SC599-11E	-2.3	-2.2	1.5
ATx635*Serena	-1.2	-1.1	1.6
ATx635*Lulu D	-21.1*	-2.3	-1.5
ATx635*RTx432	-3.4	0.9	0.9
ATx635*SC599-11E	5.7	1.4	0.2

*, ** Significant at 0.05 and 0.01 probability level, respectively.

Table C11 Additive effects (a) and average line heterosis effects (h) for agronomic characters in sorghum over all locations in Kenya in 1992/93.

Cultivar	Grain yield		Threshing percent		1000-seeds weight		Days to 50% anthesis		Plant height		Panicle length		Panicle exsertion	
	a	h	a	h	a	h	a	h	a	h	a	h	a	h
BTx630	-856.2**	-488.5	-11.5**	1.9	1.1	-0.3	3.0**	1.1	13.7**	-15.7**	1.3**	0.1	1.1	-4.2**
BTx631	-866.5*	-430.6	-3.8*	-2.6	-1.5*	-0.1	5.9**	0.5	1.4	-7.9	2.3**	0.4	-1.7	-4.2**
BTx3197	80.9	-294.9	2.9	-3.1	1.7*	-0.2	-0.5	0.8	1.7	-18.6**	-2.7**	-0.3	3.8**	-1.9
BTx635	-556.3	88.2	3.6*	-4.5*	-2.5**	0.3	2.5**	1.4*	1.3	-3.5	-1.0*	1.0*	0.1	-1.7
Serena	2525.2**	436.1	10.5**	1.1	3.2**	0.1	-3.3**	-2.1**	19.7**	36.3**	-3.3**	0.0	-4.9**	3.9**
Lulu D	881.8*	-54.6	4.3*	-2.3	-3.5**	1.2	1.1	-1.5*	-10.7*	5.7	-0.4	-0.7	-8.9**	5.9**
RTx432	-791.3*	564.8	-3.7*	4.2*	2.1**	-0.2	-4.7**	-0.3	-14.8**	2.6	-0.4	-0.3	1.9	1.7
SC599-11E	-417.6	179.5	-2.3	5.3**	-0.5	-0.7	-4.0**	0.1	-12.2**	1.2	4.2**	-0.2	8.6**	0.5

*, ** Significant at 0.05 and 0.01 level of probability, respectively.

Table C12. Specific heterosis effects in single crosses (h) of sorghum for agronomic characters over all locations in Kenya in 1992/93.

Cultivar	Grain yield	Threshing percent	1000-seed weight	Days to 50% anthesis	Plant height	Panicle length	Panicle exsertion
ATx631*BTx630	-558.6	-0.5	2.0	0.8	-13.8	-0.4	-0.3
ATx3197*BTx630	308.4	1.6	0.3	0.4	5.0	-0.7	0.4
ATx3197*BTx631	157.9	2.1	-0.5	-1.4	-8.5	-0.3	-0.4
ATx635*BTx3197	546.9	-0.1	0.8	0.3	-4.7	0.6	-3.0
ATx635*BTx630	-308.0	-3.4	-1.4	0.8	7.7	1.4	0.2
ATx635*BTx631	-146.7	0.4	-1.3	-0.8	-2.1	-0.7	3.1
ATx630*Serena	-918.6	-1.3	-0.5	0.7	14.3	0.0	-0.2
ATx630*Lulu D	426.8	2.5	0.0	-0.9	-8.2	0.3	0.6
ATx630*RTx432	298.2	1.6	0.4	-0.8	6.2	-0.2	-0.7
ATx630*SC599-11E	751.9	-0.5	-0.9	-0.9	-1.4	-0.4	0.0
ATx631*Serena	366.4	1.3	-0.1	-0.6	4.5	0.2	-0.8
ATx631*Lulu D	224.8	-3.2	1.1	-0.4	8.0	1.0	1.4
ATx631*RTx432	-78.5	0.3	-1.3	0.9	-4.6	-0.3	-1.1
ATx631*SC599-11E	34.7	-0.4	0.1	1.5	-7.2	0.3	-1.9
ATx3197*Serena	-106.8	-1.1	1.4	0.0	3.3	1.6	0.5
ATx3197*Lulu D	-795.0	-1.7	-0.5	2.1	3.8	0.3	0.6
ATx3197*RTx432	571.7	-0.3	-0.4	-1.4	7.3	-0.3	1.0
ATx3197*SC599-11E	-683.2	-0.4	-0.2	0.0	-6.3	-1.2	0.9
ATx635*Serena	659.0	1.2	0.1	-0.1	-7.0	-1.8	0.4
ATx635*Lulu D	143.4	2.4	-0.6	-0.8	-18.0	-1.2	-2.6
ATx635*RTx432	-791.4	-1.6	1.3	1.3	-1.3	0.7	0.9
ATx635*SC599-11E	-103.3	1.2	1.0	-0.6	9.0	1.3	1.0

APPENDIX D

PREDICTED THREE-WAY HYBRIDS GRAIN YIELD

Table D1. Predicted three-way hybrid means for grain yield using Jenkins' (1934) Method B in 1991 and 1992 at four locations in Texas.

	1991				1992				Over all
Entry†	CStn‡	Hway	Corp	Chill	CStn	Hway	Corp	Chill	Texas
					kg/ha				
(3*1)*6	4578	7388	6351	3555	3635	7411	3857	6088	5358
(3*1)*7	4100	8836	9019	3908	3780	8455	3112	8317	6386
(3*1)*8	5839	8540	7216	3463	3266	8317	4491	6902	6005
1*(4*6)	4164	7483	6545	3599	2988	7446	4028	6390	5342
1*(4*7)	4695	7665	7974	3972	3248	8461	4906	7182	5929
1*(4*8)	5400	7976	7253	3831	3633	8387	4822	6568	5986
2*(3*6)	4447	7638	6521	3518	5411	7299	3733	6902	5683
2*(3*8)	4925	7831	6984	3392	5545	6918	3526	6935	5757
2*(3*7)	5047	8243	7843	3029	4414	7778	4493	7123	5997
2*(4*6)	5126	7688	5708	3731	4947	8467	3837	7014	5815
3*(4*7)	-	-	-	-	-	-	-	-	-
(2*1)*6	4657	7340	6064	3975	3905	8073	3650	6806	4797
(2*1)*8	5135	8025	7237	3980	4684	8634	4248	7018	6277
(3*5)*7	-	-	-	-	-	-	-	-	-
(3*5)*8	-	-	-	-	-	-	-	-	-
r	0.20	0.34	0.71**	0.03	0.03	0.17	0.31	0.72**	0.25

*, ** Significant at 0.05 and 0.01 probability levels, respectively.
† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 B_2Tx632, 4 $B_2$8602, 5 RTx430, 6 RTx432, 7 SC103-11E, and 8 SC599-11E.
‡ Locations : CStn- College Station, Hway- Halfway, Corp- Corpus Christi, and Chill- Chillicothe.
r= Coefficient of correlation between the observed values and the predicted values.

Table D2. Observed and predicted sorghum three-way cross hybrids mean grain yield for Kibos using five methods of prediction during 1992.

	Grain yield	Predicted grain yield kg ha^{-1} (method)				
Entry	observed	1	2	3	4	5
(2*1)*5	4873	5277	5005	5683	2932	2686
(2*1)*6	1703	4556	4482	2856	2210	1965
(2*1)*7	4672	3610	3534	3420	1264	1019
(2*1)*8	2093	3804	2312	3373	1458	1213
(3*1)*5	6219	5407	5107	5474	3615	2816
(3*1)*6	5583	4686	2845	2647	2893	2095
(3*1)*7	3319	3740	3010	3211	1947	1149
(3*1)*8	4400	3934	3536	3164	2141	1343
(4*1)*5	6686	5078	5137	5749	3700	2487
(4*1)*6	6369	4357	2872	2922	2978	1766
(4*1)*7	3708	3410	3760	3486	2032	820
(4*1)*8	5301	3605	3827	3439	2227	1014
(3*2)*5	7119	5531	5793	5181	4360	2940
(3*2)*6	5430	4809	2403	2353	3638	2218
(3*2)*7	5046	3863	2644	2918	2692	1272
(3*2)*8	3080	4058	2482	2871	2886	1467
(4*2)*5	4480	5202	5823	5456	3026	2611
(4*2)*6	4762	4480	2431	2628	2305	1889
(4*2)*7	4904	3534	3394	3193	1358	943
(4*2)*8	4108	3728	2774	3146	1553	1137
(4*3)*5	5732	5332	5925	5247	3950	2741
(4*3)*6	5590	4610	794	2420	3228	2019
(4*3)*7	5220	3664	2870	2984	2282	1073
(4*3)*8	5317	3858	3998	2937	2477	1268
r		0.47*	0.63**	0.86**	0.49*	0.47*

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

† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.

r = coefficient of correlation for observed mean yield and predicted values.

Table D3. Observed and predicted sorghum three-way cross hybrids mean grain yield for Kiboko using five methods of prediction during 1992.

Entry	Grain yield observed	Predicted grain yield kg ha^{-1} (method) 1	2	3	4	5
(2*1)*5	2889	4142	2389	3690	2111	2139
(2*1)*6	3667	3475	3417	3156	1445	1472
(2*1)*7	2222	2531	3056	2559	500	528
(2*1)*8	3000	2531	3333	2781	500	528
(3*1)*5	3222	4225	3056	3288	2417	2222
(3*1)*6	3111	3558	2500	2747	1750	1556
(3*1)*7	5889	2614	2556	2149	806	611
(3*1)*8	3333	2614	2444	2372	806	611
(4*1)*5	2778	4169	3944	3747	2500	2167
(4*1)*6	3333	3503	3500	3205	1833	1500
(4*1)*7	4000	2558	1944	2608	889	556
(4*1)*8	2889	2558	3000	2830	889	556
(3*2)*5	3333	4308	3444	3642	3056	2306
(3*2)*6	3000	3642	2806	3101	2389	1639
(3*2)*7	3889	2697	3167	2504	1444	694
(3*2)*8	3556	2697	2556	2726	1444	694
(4*2)*5	5000	4253	4333	4101	3000	2250
(4*2)*6	3889	3586	3806	3559	2333	1583
(4*2)*7	2556	2642	2556	2962	1389	639
(4*2)*8	4222	2642	3111	3184	1389	639
(4*3)*5	3222	4336	5000	3691	3500	2333
(4*3)*6	2722	3669	2889	3149	2833	1667
(4*3)*7	2333	2725	2056	2552	1889	722
(4*3)*8	3889	2725	2222	2774	1889	722
r		-0.05	0.10	-0.04	-0.04	-0.05

*, ** Significant at 0.05 and 0.01 probability levels, respectively.
† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.
r = coefficient of correlation for observed mean yield and predicted values.

Table D4. Observed and predicted sorghum three-way cross hybrids mean grain yield for Kakamega long rainy season using five methods of prediction during 1992.

	Grain yield	Predicted grain yield kg ha^{-1} (method)				
Entry	observed	1	2	3	4	5
(2*1)*5	3497	2675	3989	4118	2580	2273
(2*1)*6	2217	1949	816	1210	1854	1547
(2*1)*7	1897	1654	2059	1787	1559	1252
(2*1)*8	2290	1524	1663	1412	1429	1122
(3*1)*5	4463	3124	4327	4657	1952	2722
(3*1)*6	1737	2398	1564	1750	1226	1996
(3*1)*7	1051	2103	2744	2327	931	1701
(3*1)*8	1617	1973	2049	1952	801	1571
(4*1)*5	5294	3022	3367	4310	2193	2620
(4*1)*6	1101	2296	1386	1402	1467	1894
(4*1)*7	1077	2001	2556	1979	1172	1599
(4*1)*8	1162	1871	1987	1604	1042	1469
(3*2)*5	3366	3143	5372	4429	2702	2741
(3*2)*6	1546	2417	1538	1521	1981	2015
(3*2)*7	3446	2122	1521	2098	1686	1720
(3*2)*8	1444	1992	1340	1723	1556	1590
(4*2)*5	4402	3041	4412	4081	2636	2639
(4*2)*6	1006	2315	1359	1174	1910	1913
(4*2)*7	1372	2020	1332	1750	1615	1618
(4*2)*8	2247	1890	1277	1375	1485	1488
(4*3)*5	4354	3490	4749	4621	3129	3088
(4*3)*6	1529	2764	2108	1713	2403	2362
(4*3)*7	1563	2469	2017	2290	2108	2067
(4*3)*8	2511	2339	1664	1915	1978	1937
r		0.69**	0.70**	0.85**	0.65**	0.69**

*, ** Significant at 0.05 and 0.01 probability levels, respectively.
† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.
r = coefficient of correlation for observed mean yield and predicted values.

Table D5. Observed and predicted sorghum three-way cross hybrids mean grain yield for Kakamega short rainy season using five methods of prediction during 1992/93.

	Grain yield	Predicted grain yield kg ha^{-1} (method)				
Entry	observed	1	2	3	4	5
(2*1)*5	3755	-	5998	6512	3245	3013
(2*1)*6	2082	-	3500	3174	2072	1841
(2*1)*7	1744	-	1624	3228	911	680
(2*1)*8	5274	-	3385	1595	1594	1363
(3*1)*5	3734	-	5096	6366	4688	3298
(3*1)*6	7148	-	2506	3029	3516	2126
(3*1)*7	8206	-	3730	3082	2355	965
(3*1)*8	3441	-	2596	1450	3038	1648
(4*1)*5	4919	-	6632	7268	4324	3148
(4*1)*6	4141	-	5449	3930	3151	1975
(4*1)*7	3881	-	2777	3984	1991	815
(4*1)*8	2099	-	2673	2351	2674	1498
(3*2)*5	3338	-	7255	6620	3502	3062
(3*2)*6	7451	-	1763	3282	2330	1890
(3*2)*7	4460	-	4543	3336	1169	729
(3*2)*8	2975	-	1381	1703	1852	1412
(4*2)*5	5213	-	8792	4183	3310	1739
(4*2)*6	7272	-	4706	4237	2149	578
(4*2)*7	2556	-	2556	2962	1389	639
(4*2)*8	6103	-	1458	2604	2832	1261
(4*3)*5	3984	-	7889	7376	5172	3196
(4*3)*6	5449	-	3712	4038	4000	2023
(4*3)*7	2068	-	5695	4092	2839	863
(4*3)*8	3800	-	669	2459	3522	1546
r		-	0.00	-0.02	0.12	-0.01

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

† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.

r = coefficient of correlation for observed mean yield and predicted values.

Table D6. Observed and predicted sorghum three-way cross hybrids over all mean grain yield at four locations in Kenya using five methods of prediction during 1992/93.

Entry	Grain yield observed	Predicted grain yield kg ha^{-1} (method) 1	2	3	4	5
(2*1)*5	3754	4384	4345	5003	2717	2528
(2*1)*6	2417	3562	3054	2599	1895	1706
(2*1)*7	2634	2725	2568	2748	1059	870
(2*1)*8	3164	2912	2673	2290	1245	1056
(3*1)*5	4510	4620	4396	4947	3455	2765
(3*1)*6	4395	3799	2354	2543	2633	1943
(3*1)*7	4616	2962	3010	2692	1797	1106
(3*1)*8	3198	3149	2656	2234	1984	1293
(4*1)*5	4919	4461	4770	5268	3179	2605
(4*1)*6	3736	3639	3302	2865	2357	1784
(4*1)*7	3166	2803	2759	3014	1521	947
(4*1)*8	2863	2990	2872	2556	1708	1134
(3*2)*5	4289	4618	5466	4970	3406	2762
(3*2)*6	4357	3796	2127	2564	2584	1940
(3*2)*7	4210	2960	2969	2714	1748	1104
(3*2)*8	2764	3146	1940	2256	1935	1291
(4*2)*5	4774	4459	5840	5290	3286	2603
(4*2)*6	4232	3637	3075	2886	2464	1781
(4*2)*7	2767	2800	2718	3035	1628	945
(4*2)*8	4170	2987	2155	2577	1815	1131
(4*3)*5	4323	4695	5891	5234	3938	2840
(4*3)*6	3823	3874	2376	2830	3116	2018
(4*3)*7	2796	3037	3160	2979	2279	1181
(4*3)*8	3879	3224	2138	2521	2466	1368
r		0.63**	0.47*	0.53*	0.66**	0.63**

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

† The parents in a particular cross are identified by number; 1 BTx630, 2 BTx631, 3 BTx3197, 4 BTx635, 5 Serena, 6 Lulu D, 7 RTx432, and 8 SC599-11E.

r = coefficient of correlation for observed mean yield and predicted values.