Evaluation of local maize collections for drought tolerance

E. Y. DANQUAH, P. Y. K. SALLAH, E. T. BLAY & F. ABOAGYE-NUAMAH
(E. Y. D., E. T. B. & F. A.-N.: Department of Crop Science, Faculty of Agriculture, University of Ghana, Legon, Ghana; P. Y. K. S.: Crops Research Institute, CSIR, Fumesua, Kumasi, Ghana)

ABSTRACT

One hundred local maize collections, including two improved varieties, Dobidi and Okomasa, were evaluated at Legon and Fumesua in Ghana over 2 years (1997 and 1998) during the dry seasons to determine the productivity of local maize varieties under moisture stress, compare the performance of local and improved varieties under moisture stress, and to select some of the accessions for further evaluation. Drought affected the plants significantly under the conditions of the experiment. There were significant differences among the 100 accessions in the mean expression of the number of days to silking, ear height, number of plants harvested, number of ears harvested, stover weight, 1000-seed weight, and grain yield. Analysis of variance showed significant effects of environment (location × year), accessions, and accessions × environment interaction for all of the characters studied. Significant correlations were observed between the number of ears harvested and grain yield (r=0.6), and between silking and grain yield (r=-0.4). Most of the local collections performed better than the improved varieties, which did not rank among the top 20 accessions. The authors are currently evaluating some of the promising accessions under drought and irrigated conditions. It is suggested that genes for drought tolerance be identified and introgressed into the improved varieties.

Original scientific paper. Received 10 Apr 2000; revised 30 May 2001.

RÉSUMÉ

DANQUAH, E. Y., SALLAH, P. Y. K., BLAY, E. T. & ABOAGYE-NUAMAH, F.: *Evaluation des collections de maïs local pour la tolérance à la sècheresse.* Cent collections de maïs local, comprenant deux variétés améliorées, Dobidi et Okomasa étaient évaluées à Legon et Fumesua au Ghana sur 2 années (1997 et 1998) pendant les saisons sèches; pour déterminer la productivité des variétés de maïs local sous les tensions d'humidité et pour sélectionner quelques-une des accessions pour l'évaluation supplémentaire. La sècheresse affectait les plantes considérablement sous les conditions de l'expérience. Il y avait des différences considérables parmi les 100 accessions dans l'expression moyenne de nombre de jours à l'apparition de soies, la taille d'épi, nombre de plantes moissonnées, nombre d'épi moissoné, poids de fourrage, poids de 1000-graine et le rendement de grain. L'analyse de variance révélait des effets considérables de l'environnement (location × année), accessions et accessions × interaction environnementale pour tous les caractères étudiés. Les corrélation considérables étaient observées entre le nombre d'épi moissonné et le rendement de grain (r = 0.6) et entre l'apparition de soie et le rendement de grain (r = -0.4). Beaucoup de collections locales rendaient mieux que les variétés améliorées, qui ne sont pas comptées parmi les 20 premières accessions. Les auteurs évaluent à présent les quelques accessions promettantes sous les conditions de sècheresse et d'irrigation. Il est sugéré que les gênes pour la tolérance à la sècheresse soient identifiés et introgressé dans les variétés améliorées.

Introduction

Maize (*Zea mays* L.) is the third most important cereal crop after wheat and rice in terms of production in the world (Ochse *et al.*, 1996). In Ghana, it is the most important cereal in terms of production and consumption (PPMED, 1992). The crop tolerates a wide range of environmental conditions, but grows well in warm sunny climates with adequate moisture (Purseglove, 1992). Maize is grown almost everywhere from the coastal belt across the forest transition, Guinea savanna to the north east corner (NARP, 1993). It constitutes the primary staple in the areas of production (PPMED, 1992), and features prominently in animal feed and as industrial raw material (NARP, 1993). Production, however, falls short of demand, despite the importance of the crop. Yields are very low throughout the country, on average 1.2 t/ha, but could be as low as 0.5 t/ha compared to over 5.0 t/ha in parts of northern and southern Africa (PPMED, 1992), 8.0 t/ha in Indonesia (Krisdiana & Heriyanto, 1992), 6.3 t/ha in Julin Province of China (Qiao *et al.*, 1996), and 7.0-8.9 t/ha in Ethiopia (Onyango & Ngeny, 1997).

One of the major limiting factors of maize production in the savanna zones of Ghana is drought (moisture stress), which is the most important factor limiting the growth of most plants (Carrow, Shearman & Watson, 1990; Dai *et al.*, 1990; Ober, 1991; Donatelli, Hammer & Vanderlip, 1992; Park & Sinclair, 1993; Lecoeur & Sinclair, 1996). The yields of maize in the forest and transitional zones are also very low during the minor growing season due to erratic and inadequate rainfall (NARP, 1993). In most areas in the north-eastern and north-western corner of the country, it is no longer possible to get an economic crop as a result of severe drought. Farmers are, therefore, shifting to the cultivation of sorghum and millet on most lands previously cultivated with maize.

Moisture stress affects the growth of maize at all stages of development, directly and indirectly (Tollenaar, 1977; Fischer & Palmer, 1983; Kiniry & Ritchie, 1985; Jones, Roesslar & Quatter 1985; Gu *et al.*, 1989; Dai *et al.*, 1990; Ober, 1991; Jacobs & Pearson, 1991; Schussler & Westgate, 1991; Celiz *et al.*, 1995; Norman & Searle, 1995; Agrama & Moussa, 1996; Ribaut *et al.*, 1996; Chen-Zong-Long, 1996). Significant reductions in yield caused by drought commonly occur in maize production fields throughout the world. The estimated losses are about 15 per cent, about 1.2 million tons annually in Indonesia (Dahlan, Mejaya & Slamet, 1997); 0.79 t/ha or 68 per cent in the commercial farming sector, and 1.69 t/ha or 37 per cent in the large-scale commercial sector in Zimbabwe (Machida, 1997); 10-75 per cent in Asia (Logrono & Lothrop, 1997); and 1.2 million tons in Argentina (Eyherabide *et al.*, 1997).

One strategy to reduce water stress is to use drought-resistant species and cultivars (Carrow *et al.* 1990). The need for genotypes that can tolerate drought cannot, therefore, be overemphasized. The improvement of drought resistance is suggested as a desirable breeding objective in crops such as wheat (Blum, 1983), cowpea (Gwathwey & Hall, 1992), lentils (Erskine *et al.*, 1994), cotton (Saranga, Flash & Yakir, 1998), turfgrass (Kein & Kronstad, 1979), and maize (Qiao *et al.*, 1996; Logrono & Lothrop, 1997; Edmeades *et al.*, 1999). Drought-tolerant varieties will provide a highly cost-effective means of stabilizing yields and farmers' income. The Crops Research Institute (CRI) has in recent years released many improved varieties of maize, but none of them is able to withstand moisture stress (NARP, 1993).

The objectives of this study were to determine the productivity of local maize collections under moisture stress, compare the performance of local accessions and improved varieties under moisture stress, and to select drought-tolerant local accessions from the collection for further evaluation.

Materials and methods

The study was conducted in 2 years (1997 and 1998) at two locations in Ghana, University of Ghana Farms, Legon and Crops Research Institute, Fumesua near Kumasi. The soils at Legon belong to the Nyibenya-Haatso series of the savanna ochrosols. They are light textured, free draining, and easy to work with, but are inherently poor in nutrients. The Fumesua soils are the sedentary, red, brown and yellow-brown gritty clays belonging to the Kumasi series of the forest ochrosols. They are relatively well drained and easily tilled, but become susceptible to drought when cleared for agriculture (Brammer, 1960).

The study was carried out between November and March in both years. One hundred accessions of maize including two improved varieties, Dobidi and Okomasa, were used in the study. The experiments were arranged in randomized complete block design with two replications. Each replicate comprised five blocks containing 20 entries. Block size was 5 m × 14.25 m. Two seeds were sown per hill. Plants were thinned to one per hill, 2 weeks after crop establishment. Weeds were controlled first by applying atrazine at a rate of 3.6 kg a.i ha^{-1}, 2 days after sowing and thereafter, by hand weeding as and when required. One week after establishment, NPK (20-20-0) was applied again at a rate of 2.34 g/plant, i.e. 50 kg/ha. Sulphate of ammonia was applied again at the rate of 50 kg/ha 6 weeks after sowing. Cymethoate (at a rate of 1 l in 200 l of water ha^{-1}) was sprayed 3 and 7 weeks after planting to control stem borers. Aldrin (at the rate of 400 ml in 200 l of water ha^{-1}) was sprayed 8 weeks after planting to control termites. The plants were irrigated for 45 days. Thereafter, watering was withheld but plants were rescued from total collapse by watering when they showed signs of wilting.

Data collected included number of days from sowing to 50 per cent silking, ear height (cm), i.e. height of the plant at the highest ear, number of plants harvested, number of ears harvested, stover weight, 1000-seed weight, and grain yield (weight of all shelled grains/number of plants harvested (g). Grain yield was estimated by using the two central rows.

Statistical analysis

The range, mean, and standard error of the means for each character were computed. The data were then analysed with the analysis of variance which was performed on the following variables: number of days to silking, ear height, number of plants harvested, number of ears harvested, stover weight, 1000-seed weight, and grain yield. The genotypic differences were assessed based on 5 and 1 per cent levels of probability, to test for significant differences in location, year, accession, location by year (environment) and environment by accession (location × year × accession) interactions. The hypothesis of interest was that there were no significant differences among the 100 accessions in the mean expression of the characters that were studied. Correlations among characters were also calculated.

Results and discussion

The analysis of variance showed that location and year effects were highly ($P < 0.01$) significant for all the traits measured (Table 1). The location × year interaction was also highly significant for ear height, 1000-seed weight, ears harvested, and grain yield.

The location × accession interaction was highly ($P < 0.01$) significant for stover weight and

TABLE 1

Mean Squares for the Sources of Variation for Seven Characters Studied Among 100 Accessions of Maize

Source of variation	*d. f. m.v.*	*Days to silking*	*Ear height*	*Plants harvested*	*Stover weight*	*1000-seed weight*	*Grain yield*	*Ears harvested*
Replications	1							
Location	1	4875.62**	75381**	18183.245**	20.38**	1142241**	414036**	421.95**
Year	1	1650.34**	48896.6**	725.805**	2.89**	1036814**	212718**	205.03**
Access	99	94.30*	975.7**	19.153**	0.21**	4872*	14363**	18.64**
Loc. × year	1	1.53	15484.6**	1.445	0.01	406793**	247045**	207.06**
Loc. × access	99	79.54*	615.4*	13.700*	0.15**	4613**	8080*	7.88*
Year × access	99	95.22*	686.7*	21.573**	0.15**	5015*	13837**	19.86**
Loc. × year × acc.	99	78.52*	707.1*	17.026**	0.12*	6963**	9365*	8.04*
Total	799							

* and ** indicate that the F tests were significant at $P<0.05$ and $P<0.01$, respectively.

1000-seed weight, and significant ($P < 0.05$) for all the other traits. The year × accession interaction was significant for days to silking, ear height and 1000-seed weight, and highly significant for plants harvested, stover weight, ears harvested, and grain yield (Table 1). The second order interaction (location × year × accession) was also significant for days to silking, ear height, stover weight, ears harvested and grain yield, and was highly significant for plants harvested and 1000-seed weight (Table 1).

The significant location × accession, year × accession, and location × year × accession interactions observed for these traits showed that the environments used for the evaluation were different. Variations in soil characteristics, including water retention capacity at the two sites, probably accounted for differences among the environments. The significant interactions also showed that the genotypes responded differently to the different environments.

Differences among the accessions were significant ($P < 0.05$) for days to silking and 1000-seed weight, and highly ($P < 0.01$) significant for ear height, plants harvested, ears harvested, stover weight, and grain yield (Table 1). The ranges, means, and standard error of the characters studied indicated that there was variability among the accessions (Table 2). There were positive correlations (Table 3) between silking and stover weight (r=0.3), ear height and grain yield (r=0.3), and number of ears harvested and grain yield (r=0.6). The correlations between number of days to silking and ear height, and number of days to silking and grain yield were negative, r=-0.03 and r=-0.4, respectively. The correlations between silking and ear height (r=-0.04), stover weight and grain yield (r=-0.02), and 1000-seed weight and grain yield (r=0.06) show that there are no clear relationships between those characters.

TABLE 2

Ranges, Means and Standard Error of the Means for the Characters Studied

Variable	*Range*	*Mean + s.e.*
Silking (days)	0 - 115	65 ± 0.33
Ear height (cm)	0 - 224	224 ± 0.98
Plants harvested	0 - 21	9 ± 0.22
Ears harvested	0 - 19	4 ± 0.12
Stover weight (kg)	0 - 2.3	0.5 ± 0.01
1000-seed weight (g)	0 - 320	110.28 ± 3.11
Grain yield (g)	0 - 551	108.14 ± 3.70

The significant negative correlation between the number of days to silking and grain yield (r=-0.4) indicates that the accessions with shorter number of days to silking yielded more grains than the accessions with relatively longer number of days. This confirms previous studies (Badu-Apraku *et al.*, 1997) that no significant correlations between grain yield, anthesis-silking interval (ASI), and ears per plant under non-stress conditions were estimated. Under drought stress, however, grain yield and ears per plant were positively correlated, and grain yield and ASI were negatively correlated. During reproductive

TABLE 3

Correlations (Pearson) Between the Characters Studied

	Silking	*Ear height*	*Plants harvested*	*Ears harvested*	*Stover weight*	*1000-weight*
Ear height (cm)	-0.04					
Plants harvested	-0.25	0.44*				
Ears harvested	-0.24	0.10	0.20			
Stover weight (kg)	0.31*	0.18	-0.24	0.18		
1000-seed weight (g)	0.12	-0.15	-0.29	0.35*	0.21	
Grain yield (g)	-0.40*	0.33*	0.43*	0.57*	-0.02	0.06

* Significant correlations

development in maize, the silks emerge 2-3 days after pollen shed (anthesis) and begin to elongate until they are pollinated. The period between anthesis and silk emergence is called the anthesis-silking interval. Under favourable conditions, pollen shed continues for 14 days or more, allowing for an overlap with silk emergence and period of receptivity. The time of silking and pollination is the time of peak water demand, which continues to grain filling. Under hot dry weather and drought conditions, the period of anthesis is shortened and there is delayed silk emergence. The overlap between the anthesis and silking period, and hence the period for successful pollination, becomes short.

It has been observed in several studies that when drought stress occurs just before or during flowering period, a delay in silking was observed. An increase in number of days to silking results in an increase in the length of ASI and a decrease in grain yield (Bolanos & Edmeades, 1988; Pons *et al.*, 1995; Ribaut *et al.*, 1996). Thus, when pollination coincides with adverse weather, there may be more pronounced pollination failure and drastic grain yield reduction as shown by the negative correlation between silking and grain yield.

The positive correlation between the ear height and grain yield (r=0.3) also indicates that taller plants produced more grains.

The number of plants and ears harvested was positively correlated with grain yield, r=0.43 and 0.57, respectively. This implies that the more plants and ears that will be harvested, the more the grains that will be obtained. This agrees with previous reports (Cleassen & Shaw, 1990; Hall, Lemcoff & Trupuni, 1981) that grain yield in maize is mostly dependent on variations in the number of kernels harvested. However, growth conditions during grain filling could also affect grain yield by affecting dry matter allocation to kernels (Tollenaar, 1977; Tollenaar & Daynard, 1978; Uhart & Andrade, 1995). It is, therefore, important to select plants that will use water efficiently and hence be able to produce ears under water stress. Water is essential for growth and maintenance, and the plants are able to carry out photosynthesis efficiently to produce photosynthates, which accumulate in the plant and later in the ear and kernel during reproductive growth.

The negative correlation between stover weight and grain yield (r=-0.02), though not significant, shows that the ability of the plant to yield much grain depends on its ability to convert photosynthates into reproductive growth instead of dry matter accumulation in the plant. This is because after pollination, vegetative growth ceases, followed by rapid ear growth and dry matter accumulation in the kernel. Dry matter accumulation in kernels depends, among other factors, on the availability of assimilate reserve from other plant parts (Tollenaar, 1977). A shortage in assimilate supply or unfavourable thermal environment during this phase affects the potential kernel size (Frey, 1981; Reddy & Daynard, 1983; Jones, Roessler & Quattar, 1985).

Several authors have suggested that the reduction in assimilate supply to maize kernels induces early black layer formation, affecting grain-filling duration and kernel size (Daynard, 1972; Afuakwa, Crookston & Jones, 1984; Tollenaar & Daynard, 1978) and eventually grain yield. Ober (1991) states that decreased grain yield in response to post-pollination drought is primarily due to decreased endosperm dry matter accumulation, especially of grain in apical ear region. Inhibited cell division during early grain development is a contributor to such decrease in grain mass, and that this environmental response is mediated by changes in growth regulator level in the endosperm.

Based on the observations and results of the study, it can be concluded that drought stress affected the plants significantly under the conditions of the experiment. The significant results indicate real differences among the 100 accessions for the characters studied at the various locations. In selecting an accession for drought tolerance, the grain yield components, which include the number of cobs/plant, grain weight, and ASI, must be considered. The authors are currently evaluating some of the selected accessions under moisture stress and irrigated conditions to estimate the effect of drought on the local collections. The local accessions possibly have genes for drought tolerance, and it is suggested that these genes be identified and introgressed into the improved varieties (Table 4).

TABLE 4

Accessions that Performed Better Under All Environments for the Characters Studied

Entry no.	*Entry name*	*Days to silking*	*Ear height (cm)*	*Grain yield (g/ha)*	*Stover weight (kg/ha)*
A1	LA92/009[B]	62	90.87	131.4	0.537
B1	LA92/023	62	100.37	185.0	0.825
F6	LA92/050	62	113.37	223.5	0.950
F7	LA92/001	62	126.62	225.3	0.787
F9	LA92/021	60	109.12	168.7	0.550
H2	AD92/001	60	103.25	198.6	0.650
H1	LA92/094	58	96.75	192.9	0.612
H5	LA92/020	65	110.50	145.9	0.975
H10	LA92/033	60	104.75	182.4	0.737
C8	LA92/016	64	100.50	149.5	0.712
A10	AD92/024	66	116.75	154.3	0.875
G8	LA92/019	59	93.50	172.2	0.437
G10	LA92/034	59	107.12	158.5	0.625
G4	LA92/046	60	109.62	176.3	0.625
G5	LA92/004	61	99.25	147.2	0.525
G7	AA92/001	66	129.87	197.4	1.100
B10	LA92/042	65	107.50	129.8	0.812
H4	LA92/024	61	114.25	146.8	0.600
F8	LA92/048	60	105.00	124.6	0.587
B5	AD92/0035[B]	64	98.62	149.8	0.800

REFERENCES

Afuakwa, J. J., Crookston, R. K. & Jones, R. J. (1984) Effects of temperature and sucrose availability in kernel black layer development in maize. *Crop Sci.* **24**, 285-288.

Agrama, H. A. S. & Moussa, M. E. (1996) Mapping QTLS in breeding for drought tolerance in maize. *Euphytica* **91**, 89-97.

Badu-Apraku, B., Diallo, A. O., Fajemisin, J. M. & Fakorede, M. A. B. (1997) Progress in breeding for drought tolerance in tropical early maturing maize for the semi-arid zone of West and Central Africa. In *Developing drought - and low N-tolerant maize,* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson, and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT. 1997.

Blum, A. (1983) Genetic and physiological relationship in plant breeding for drought resistance. *Agric. Water Mgt* **7**, 195-205.

Bolanos, J. & Edmeades, G. O. (1988) CIMMYT's strategy in breeding for drought tolerance in tropical maize. *Paper presented at the International Conference on Dry Land Farming,* Amarillo, Texas, August 15-19, 1998.

Brammer, H. (1960) Interim report on the reconnaise soil survey of the Accra Plains. *Tech. Rep.* **42.** Ministry of Agriculture, Ghana.

Carrow, R. N., Shearman, R. C. & Watson, J. R. (1990) Turfgrass. In *Irrigation of agriculture crops Agon. Monogr. 30, ASA, CSSA and SSSA* (ed. B. A. Stewart and D. R. Nielson), pp. 889-919. Madison. WI.

Celiz, A., Presello, D., Guevara, E., Avila, L. G. & Cespedes, P. L. M. (1995) Performance of inbred lines of maize under conditions of water stress. Memorial dé la 111. *Reunion Latinoamericana y xvi Reunion dé la zona Andina dé Investigadores en maiz.* pp. 67-83. Centro dé Investigaciones Fitocogeneticas dé Pairumani; cochabambi; Bolivia.

Chen-Zong-Long (1996) Influence of drought in maize fields in South China: Strategies to overcome these constraints. In *Developing drought- and low N-tolerant maize* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT, 1997.

Cleassen, M. M. & Shaw, R. H. (1990) Water deficit effects on corn. II. Grain components. *Agron. J.* **64**, 652-655.

Dai, J. Y., Gu, W. L., Shen, X. Y., Zheng, B., Qi, H. & Cai, S. F. (1990) Effect of drought on the development and yield of maize at different growth stages. *Journal of Shenyang Agricultural University* **21** (3), 181-185.

Dahlan, M., Mejaya, M. J. & Slamet, S. (1997) Maize losses due to drought in Indonesia and sources of drought tolerance and escape. In *Developing drought- and low N-tolerant maize* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT, 1997.

Daynard, T. B. (1972) Relationship among black layer formation, grain moisture percentage and heat unit accumulation in corn. *Agron. J.* **64**, 716-719.

Donatelli, M., Hammer, G. L. & Vanderlip, R. L. (1992) Genotype and water limitation effects on phenology, growth, and transpiration efficiency in grain sorghum. *Crop Sci.* **32**, 781-786.

Edmeades, G. O., Bolanos, J., Chapman, S. C., Lafitte, H. R. & Banziger, M. (1999) Selection improves drought tolerance in tropical maize populations: 1. Gains in biomass, grain yield and harvest index. *Crop Sci.* **39** (5), 1306-1315.

Erskine, W., Tufail, M., Russell, A., Tyagi, M. C., Rahman, M. M., Saxena, M. C., Muehlbauer, F. J. & Kaiser, W. J. (1994) Current and future strategies in breeding lentil for resistance to biotic and abiotic stresses. In *Expanding the production and use of cool season food legumes. Proceedings of the Second International Food Legume Research Conference on pea, lentil, faba bean, chickpea, and grasspea* (ed. F. J. Muehlbauer), Cairo, Egypt, 12-16 April 1992, 1994, pp. 559-571. Dordrecht, Netherlands: Kluwer Academic Publishers Group.

Eyherabide, G. H., Guevara, E. & Totis-de-Zeljkovich, L. (1997) Effect of the hydrostress in maize production in Argentina. In *Developing drought- and low N-tolerant maize* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT, 1997.

Frey, N. M. (1981) Dry matter accumulation in kernel maize. *Crop Sci.* **13**, 436-439.

Fischer, K. S. & Palmer, A. F. E. (1983) Maize. In *Proc. symp. on potential productivity of field crops under different environments* (ed. IRRI), pp. 155-180. Los Banos, Philippines.

Gu, W. L., Dai, J. Y., Shen, X. Y. & Wang, C. (1989) Drought resistance of maize at different growth stages. Shenyang Agricultural University, China. *Plant-Physiology-Communications* **3**, 18-21.

Gwathwey, C. O. & Hall, A. E. (1992) Adaptation to mid-season drought of cowpea genotype with contrasting senescene traits. *Crop Sci.* **32**, 773-778.

Hall, A. J., Lemcóff, J. H. & Trupuni, N. (1981) Water stress before and after flowering in maize and its effects on yield, its components, and their detriments. *Maydica* **26**, 19-38.

Jacobs, B. C. & Pearson, C. J. (1991) Potential yield of maize determined by rates of growth and development of ears. *Fd Crop. Res.* **27**, 281-298.

Jones, R. J., Roessler, R. & Quattar, S. (1985) Thermal environment during endosperm cell division in maize: Effects on number of endosperm cells and starch granules. *Crop Sci.* **25**, 830-834.

Kein, D. L. & Kronstad, W. E. (1979) Drought resistance and dry land adaptation in winter wheat. *Crop Sci.* **19**, 574-576.

Kiniry, J. R. & Ritchie, J. T. (1985) Shade sensitive interval of kernel number in maize. *Agron. J.* **77**, 711-715.

Krisdiana, R. & Heriyanto (1992) Analysis of the hybrid and Arjuna maize production system in Kediri. In *Balai Penelitian Tanaman Pangan, Malang (Indonesia). [Report of research results of Malang Research Institute for Food Crops during 1991]. Risalah hasil penelitian tanaman pangan tahun 1991* (ed. A. Kasno, K. H. Hendroatmodjo, M. Dahlan, Sunardi and A. Winarto), pp. 70-78. Malang (Indonesia) BPTP. 1992.

Lecoeur, J. & Sinclair, T. R. (1996) Field pea transpiration and leaf growth in response to soil water deficits. *Crop Sci.* **36**, 331-335.

Logrono, M. L. & Lothrop, J. E. (1997) Impact of drought and low nitrogen on maize production in

Asia. In *Developing drought- and low N-tolerant maize* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT, 1997.

Machida, L. (1997) Estimates of yield losses in maize production due to drought in Zimbabwe. In *Developing drought- and low N-tolerant maize* (ed. G. O. Edmeades, M. Banziger, H. R. Mickelson and C. B. Pena-Valdivia). Mexico, DF (Mexico). CIMMYT, 1997.

NARP (1993) National Agricultural Research Project, pp. 1-18. In *Annual report on cereals by the commodity committee,* Accra, Ghana.

Norman, M. J. T. & Searle, P. G. E. (1995) *The origin of tropical food crops in their environment,* 2nd edn. Cambridge University Press, pp. 127-140.

Ober, E. S. (1991) Water deficit during maize endosperm development: Abscisic acid, cell division and storage protein synthesis. *Dissertation Abstracts Int. B. Sciences and Engineering* **51** (9), 4414B-4415B.

Ochse, J. J., Soule, M. J., Dijkman, M. J. & Welbery, C. (1996) The major cereals ranked in terms of production in tropical and subtropical agriculture. (Volume 11). Macmillan Company. New York.

Onyango, R. M. A. & Ngeny, J. M. A. (1997) Verification of recommended maize production package on farmers' fields in Trans-Nzoia District. In *Maize productivity gains through research and technology dissemination* (ed. J. K. Ransom, A. F. E. Palmer, B. T. Zambezi, Z. O. Mduruma, S. R. Waddington, K. V. Pixley and D. C. Jewell). Addis Ababa (Ethiopia). CIMMYT. 1997.

Park, W. I. & Sinclair, T. R. (1993) Consequences of climate and crop yield limits on the distribution of corn yields. *Rev. Agric. Econ.* **15** (3), 483-493.

Pons, J. L., Arreola, J. M., Gonzalez, M., Martinez, O. & Simpson, J. S. (1995) Induced mutations and molecular techniques for crop improvement. In *Determination of molecular markers associated with the anthesis-silking interval in maize,* pp. 37-244. International Atomic Energy, Vienna, Australia.

PPMED (1992) Policy Planning, Monitoring and Evaluation Department, Ministry of Agriculture. *Agriculture in Ghana : Facts and figures.* pp. 74-75.

Purseglove, J. W. (1992) *The uses, classification, origin, distribution cultivars, ecology and distribution of maize in tropical crops (monocotyledons).* London: Longmans. pp. 607.

Qiao, C. G., Wang, Y. J., Guo, H. A., Chen, X. J., Lui, J. Y. & Li, S. Q. (1996) A review of the advances in maize production in Julin Province during 1974-1993. *Fd Crop. Res.* **47** (1), 65-75.

Reddy, V. H. & Daynard, T. B. (1983) Endosperm characteristics associated with rate of grain filling and kernel size in corn. *Maydica* **28**, 339-355.

Ribaut, J. M., Hoisington, D. A., Deutsch, J. A., Jiang, C. & Gonzalez-de-Leon, D. (1996) Identification of quantitative trait loci under drought conditions in tropical maize. I. Flowering parameters and the anthesis silking interval. *Theoret. Appl. Gen.* **92** (7), 905-914.

Saranga, Y., Flash, I. & Yakir, D. (1998) Variation in water use efficiency and its relation to carbon isotope ratio in cotton. *Crop Sci.* **38**, 782-787.

Schussler, J. R. & Westgate, M. E. (1991) Maize kernel set at low water potential: I. Sensitivity to reduce assimilates during early kernel growth. *Crop Sci.* **31**, 1189-1195.

Tollenaar, M. (1977) Source-sink relationships during reproductive development in maize: A review. *Maydica* **22**, 49-75.

Tollenaar, M. & Daynard, T. B. (1978) Effect of defoliation on kernel development in maize: A review. *Maydica* **22**, 49-75.

Uhart, S. A. & Andrade, F. H. (1995) Nitrogen and carbon accumulation and remobilization during grain filling in maize under different source/sink ratios. *Crop Sci.* **35**, 183-190.