EVALUATION OF GROUNDNUT GERMPLASM UNDER DROUGHT AND HEAT STRESS IN SAHELIAN ZONE

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ABSTRACT

Severe drought and temperature increase are predicted to be the major consequences of climate change. Groundnut is a major crop cultivated in the Sahel zone where water and high temperature stress are serious constraints for its production. Investigating drought and heat effects on physiological traits, yield and its attributes could significantly contribute for improving groundnut productivity and consequently the incomes of farmers. A groundnut germplasm (268 genotypes) was evaluated in four trials during two years under intermittent drought and fully irrigated conditions. Drought stress reduced pod yield up to 72 % compared to 55 % at moderate temperature. The haulm yield decrease due to drought was 34 % at high temperature and 42 % under moderate temperature. Haulm yield tended to increase under high temperature. Genotype by environment interaction (GxE) was significant under well-watered (WW) and water stress (WS) treatments. The genotype and genotype by environment (GGE) biplots analyses revealed several mega environments under WW and WS treatments. The GGE biplots analyses revealed also several genotypes with high performance and stability across year and temperature environments under both WW and WS conditions. The regression analyses indicated that among several traits, only the partition rate was significantly correlated to pod yield.

Key words : Groundnut, drought, high temperature, GxE interaction, GGE biplot, adaptation

RESUME

EVALUATION DE GERMPLASM DE L'ARACHIDE EN CONDITIONS DE STRESS HYDRIQUE ET THERMIQUE EN ZONE SAHELIENNE

Les conséquences majeures du changement climatique seraient une sécheresse sévère et une augmentation de températures. En zone Sahélienne où l'arachide est principalement cultivée, le déficit hydrique et les fortes températures sont les contraintes majeures de sa production. Les investigations des effets de la sécheresse et de la chaleur sur les caractères physiologiques de l'arachide, le rendement et ses composantes pourraient contribuer significativement à améliorer sa productivité et les profits des paysans. 268 génotypes d'arachide ont été évalués en 4 expérimentations durant 2 années en conditions de sécheresse intermittente (WS) et d'irrigation normale (WW). Deux des expérimentations ont été conduites en période de forte chaleur (HT) et 2 autres en période de température modérées (MT). La baisse du rendement en gousses due à WS a atteint 72 % en HT comparativement à 55 % en MT. Le rendement en fanes qui tend a augmenté en HT, a diminué de 34 % pendant les HT et de 42 % pendant MT en conditions WS. Une interaction génotype et environnement (GxE) significative a été observée en conditions WW et WS. Les analyses biplot du génotype, génotype et environnement (GGE biplot) ont révélé plusieurs méga environnements en conditions WW et WS. Ces analyses ont révélé aussi des génotypes performants et stables à travers les années et les conditions de température sous traitements WW et WS. Le taux de partition pourrait être utilisé comme critère en sélection variétale du fait qu'il est significativement corrélé au rendement.

***Mots clés :** Arachide, sécheresse, haute température, adaptation interaction GxE, GGE biplot.*

INTRODUCTION

Climate changes will lead to severe drought and high temperature in semi arid tropics zones (Van Duivenbooden *et al.,* 2002 ; IPCC, 2007, Dimes *et al.,* 2008). Drought is estimated to cause millions in revenue losses to groundnut production (Sharma and Lavanya, 2002). Groundnut is sensitive to temperature and the optimum for most processes is between 27 and 30° C (Vara Prasad *et al.,* 1999 ; Ntare *et al.,* 1998). Drought often associated with high temperature are considered to be the two major environmental factors limiting groundnut growth and yield. It is anticipated that Climates changes in the Sahel, notably drought and high temperature, will decrease groundnut yield up to 11 to 25 % by 2025 (Van Duivenbooden *et al.,* 2002).

Plant responses to high temperature vary with species and phenological stages (Wahid *et al.,* 2007). In most plants, a high temperature affects the reproductive processes and lead to reduced crop yield. For example, the effect of daytime soil of 28 and air temperature of 38° C, from the the start of flowering to maturity of groundnut, reduced the pod yield up to 50 % (Vara Prasad *et al.,* 2000). These authors observed that day temperature above 34° C decreased fruit-set and resulted in fewer numbers of pods. However, varieties grown by farmers in the Sahel yielded well in the hot months by maintaining the partition to pods above this one in normal temperature (Greenberg *et al.,* 1992 ; Ndunguru *et al.,* 1995).

Although, under field conditions drought stress is often associated with high temperature stress in the Sahel, the impacts of drought and high temperature stress on groundnut productivity have mostly been studied independently. Previous works reported a strong relationship between the plant water status and temperature, making the separation between contributions of heat and drought stress very difficult under field conditions (Ntare *et al.,* 1998 ; Vara Prasad *et al.,* 2008). Temperature tolerance is an important component of drought resistance and a necessary attribute for varieties intended for Sahel. Because large gaps of rains that cause drought are also coupled with temperature increase period. Moreover, authors showed that heat tolerance results in improved photosynthesis, assimilate partitioning, water and nutrient efficiency use, and membrane stability (Camejo *et al.,* 2005 ; Ahn and Zimmerman, 2006 ; Momcilovic and Ristic, 2007). In order to improve groundnut productivity and to predict consequences of climate change on its production, combined effects of heat and drought on physiological traits, yield and its attributes were investigated.

The goal of this study was to identify genotypes with specific or combined tolerance to drought and heat. The specific objectives were (1) to investigate the effect of intermittent drought under moderate and high temperature on agronomic characteristics, (2) to selecte contrasting genotypes under drought in both moderate and high temperature conditions and (3) to identify traits conferring heat and/or drought tolerance.

MATERIAL AND METHODS

EXPERIMENTAL CONDITIONS

Field trials were undertaken at ICRISAT Sahelian Centre (ISC) in Sadore, Niger, 45 km south of Niamey, 13° N, 2° E. The ISC soils are arenosols (World Reference Base) with low pH, a very low water retention capacity, low inherent soil fertility and organic matter content. Two trials were conducted during the rainy seasons in 2008 and 2009 characterized by moderate temperatures (MT08 and MT09) (between August and December) and two others during the summer seasons in 2009 and 2010 characterized by high temperature (HT09 and HT10) (between February and June). In all the experiments, fertilizer NPK (15-15-15) and farm yard manure (200 kg ha^{-1}116) were incorporated to soil and the field was plowed and irrigated twice before sowing. Experiments were kept disease and insect free by regular checking and sprayed if needed with an appropriate pesticide. Hand weeding was done between 30 and 50 days after soying (DAS). Two hundred sixty eight (268) genotypes, 259 entries of the groundnut reference collection and 9 farmers preferred varieties, were evaluated. Experimental design was an incomplete randomized block design with water treatment as main factor and genotypes as sub-factor randomized within each factor and replicated five times. Each plot (2 m^2) is made of 2 rows (2 m each), with 50 cm between rows, and 10 cm between plants per row. Calcium ammonium-nitrate (200 kg ha^{-1}) and gypsum (200 kg ha^{-1}) were applied during pod formation.

IRRIGATION MANAGEMENT

In all experiments, 40 mm irrigation was provided for all plots (WW and WS) through two irrigations of 20 mm per week until flowering (30-35 DAS) using a linear movement system (Valley Irrigation 125 Inc). After this, plots were exposed to intermittent irrigation until maturity by irrigating water stress (WS) plots only once a week against two a week for well-watered (WW) plots. Decision of irrigating WW and WS plots was based on the estimated evapotranspiration by measuring leaf wilting of the WS plots. Irrigation was supplied when the wilting score of the WS plots reached a value of 3 as it's equivalent of 40 - 50 % of the WW transpiration (Ratnakumar *et al.,* 2009 ; Bhatnagar-Mathur *et al.,* 2007). Wilting symptoms was recorded early afternoon as follows :

- score 1 = no wilting symptoms ;
- score 2 = few leaves wilted in a minority of plants from the plot ;
- score 3 = a majority of plants in a plot have wilted leaves, but none has reached permanent wilting ;
- score 4 = a minority of plants show at least partial symptoms of permanent wilting ;
- score 5 = most plants show symptoms of permanent wilting ;

It is indicative of a substantial stress, not yet too severe.

MEASUREMENTS

During the crop growing period, soil temperature at 5 and 10 cm at the hottest period of the day (1 to 3 O'clock PM), the maximum (Max) and minimum (Min) air temperatures and the relative humidity were recorded daily from a meteorological station located close to the experimental field. In the moderate temperature season, temperatures were measured on soil covered by vegetation. But this vegetation was dried in high temperature season. The air temperature and relative humidity were used to determine the vapor pressure deficit (VPD) (Prenger and Ling, 2001). Time of emergence and time to flowering (50 % of the plants started flowering) were recorded before water stress application. The SPAD chlorophyll meter reading (SCMR) was measured on the third leaf (from the top of the plant) using a Minolta SPAD-502 meter (Tokyo, Japan) in the MT09 and HT10 experiments during water stress period. Time to maturity and time to harvesting were recorded. To record the maturity date, border plants were randomly picked, pods number was counted and the internal pod wall was examined. Mature pods were characterized by the blackening of the internal pod wall. At harvesting, the entire two rows (2 m^2) per plot were collected. The plants were air-dried for one week before pods were separated from the haulms along with some roots that came up with the pods on lifting. For each plot, haulm weight and pod weight were recorded. Crop growth rate (CGR, kg ha^{-1} per day), pod growth rate (PGR, kg ha^{-1} 168 per day) and partitioning (P, proportion of dry matter partitioned into pods) were estimated following a modified procedure from Williams and Saxena (1991) :

$CGR = (Hwt + (Pwt \times 1.65))/T_2)$, $PGR = (Pwt \times 1.65)/(T_2 - T_1 - 15)$, $P = R/C$

Where T_2 is the number of days from sowing to harvest, T_1 is the number of days from sowing to flowering and 15 is the number of days between the beginning of flowering and the start of pod expansion (Ntare *et al.,* 2001). Haulm weight and pod weight were converted in haulm yield (Hy) and pod yield (Py) and used to determine the total biomass ($Bt = Hy + Py \times 1.65$) (Duncan *et al.,* 1978) to adjust differences in the energy requirement for producing pod dry matter compared with vegetative part.

Harvest index (HI) was determined as a ratio of adjusted pod weight to total biomass ($HI = 1.65*Py/Bt$).

STATISTICAL ANALYSIS

The results were performed with Gensat software, version 14. Data were subjected to analysis of variance (ANOVA) procedure for a linear mixed model. The Residual Maximum Likelihood (ReML) method of Genstat was used to obtain the unbiased estimate of the variance components and the best linear unbiased predictions (BLUPs) for different parameters measured within each treatment, considering genotypes as random and replications as fixed effects. Genetic variability among accessions within treatment was assessed from the standard error of the estimate of genetic varianceσ^2 g. Two way ANOVA analyses were also performed to assess the effects of water treatment (Trt) and genotype-by-water treatment (GxTrt) interaction. Weather conditions during each trial were considered as an environment (E) and the effects of environment (E) and genotype-by environment (GxE) interaction were also assessed for the different traits measured. In this case, variation components involving genotype were considered as random effects whereas Trt, E and replication effects were considered as fixed. Genetic variability across treatments or interaction effect was assessed in a similar way as above. The fixed effect was assessed using the Wald statistic that asymptotically follows a χ^2 distribution.

RESULTS

WEATHER

VPD of HT09 (3.68 kPa) and HT10 (3.66 kPa) were higher than VPD of MT08 (2.0 kPa) and MT09 (1.8 kPa) (Figure 1A). The highest temperature (41° C in average) was also observed during high temperature experiments (Figure 1B). The soil temperatures recorded at 5 cm reached 49° C with high temperature compared to 42° C with moderate temperature in season experiments. At 10 cm, the soil temperature in the high temperature season was also higher than this one in moderate temperature season (Figure 1C).

WATER TREATMENT, GENOTYPE AND GENOTYPE BY WATER TREATMENT INTERACTION

268 genotypes for both HT09 and HT10 experiments revealed, when using Analyses of variance (ANOVA) significant effects on water treatment (Trt), genotype (G) and genotype by treatment (GxTrt) for pod yield (Py), haulm yield (Hy) and harvest index (HI) of the (Table 1). The magnitude (F value) of genotype and genotype by water treatment effects was similar for each of the traits in both 2009 and 2010 years. Under fully irrigated conditions, mean for pod yield in the high temperature season was statistically similar to this one in moderate temperature. Pod yield ranged from 110 to 340 g m^{-2} under WW conditions and from 40 to 170 g m^{-2} under WS treatment. The haulm yield in the high temperature was somewhat higher than in the moderate temperature seasons, especially in the HT09 trial (Figure 2). HI revealed slightly higher values (0.38 : MT08 and 0.37 : MT09) in moderate temperature season than in high temperature season (0.25 : HT09 and 0.34 : HT10). The three agronomic traits, pod yield, haulm yield and HI, decreased significantly under drought conditions in both moderate temperature and high temperature experiments (Figure 2). For the pod yield, the decrease due to drought stress was lower in the MT08 (55 %) and MT09 (38 %) than in the HT09 (72 %) and HT10 (59 %) seasons (Table 2). Drought stress decreased highly the HI under the high temperature seasons (HT09 : 50 %, HT10 : 33 %) than under the moderate temperature seasons (MT08 : 25 %, MT09 : 25 %). This was not the case for the haulm yield which decreased less in the high temperature seasons (34 and 11 % respectively) than in the moderate temperature seasons (42 and 31 % respectively) (Table 2).

GENOTYPE AND GENOTYPE BY ENVIRONMENT (GGE) BIPLOT ANALYSIS

ANOVA analysis indicated that large GxE took place (Table 3), therefore, several GGE biplot analyses were performed to reveal the existence of mega environments and identify superior high yielding genotypes under WW and WS conditions within and across moderate and high temperature seasons. GGE biplot represents graphically the genotype (G) main effects plus genotype-by-environment interaction (G×E) effects (Figure 3). It also shows each genotype's position across the environments (MT08, MT09, HT09, HT10) based on its mean performance and stability. Under WW conditions, four mega environments were observed while there were three mega environments under WS conditions. The existence of mega environments under both WW and WS water regimes indicates that genotypes behaved differently across environments. Figure 3 shows also that genotypes located at the vertex of the polygon were the better performing genotypes (highest yielding) in each environment. In addition to the specific adaptation, genotypes like 111 and 205 seemed to adapt to both moderate and high temperature environments. Thus, based on GGE biplot analyses for ranking the genotypes, the most adapted (highest yielding) and poorest adapted (lowest yielding) in moderate (MT), high (HT) and across both moderate and high temperature (MTHT) environments were selected and presented in Table 4.

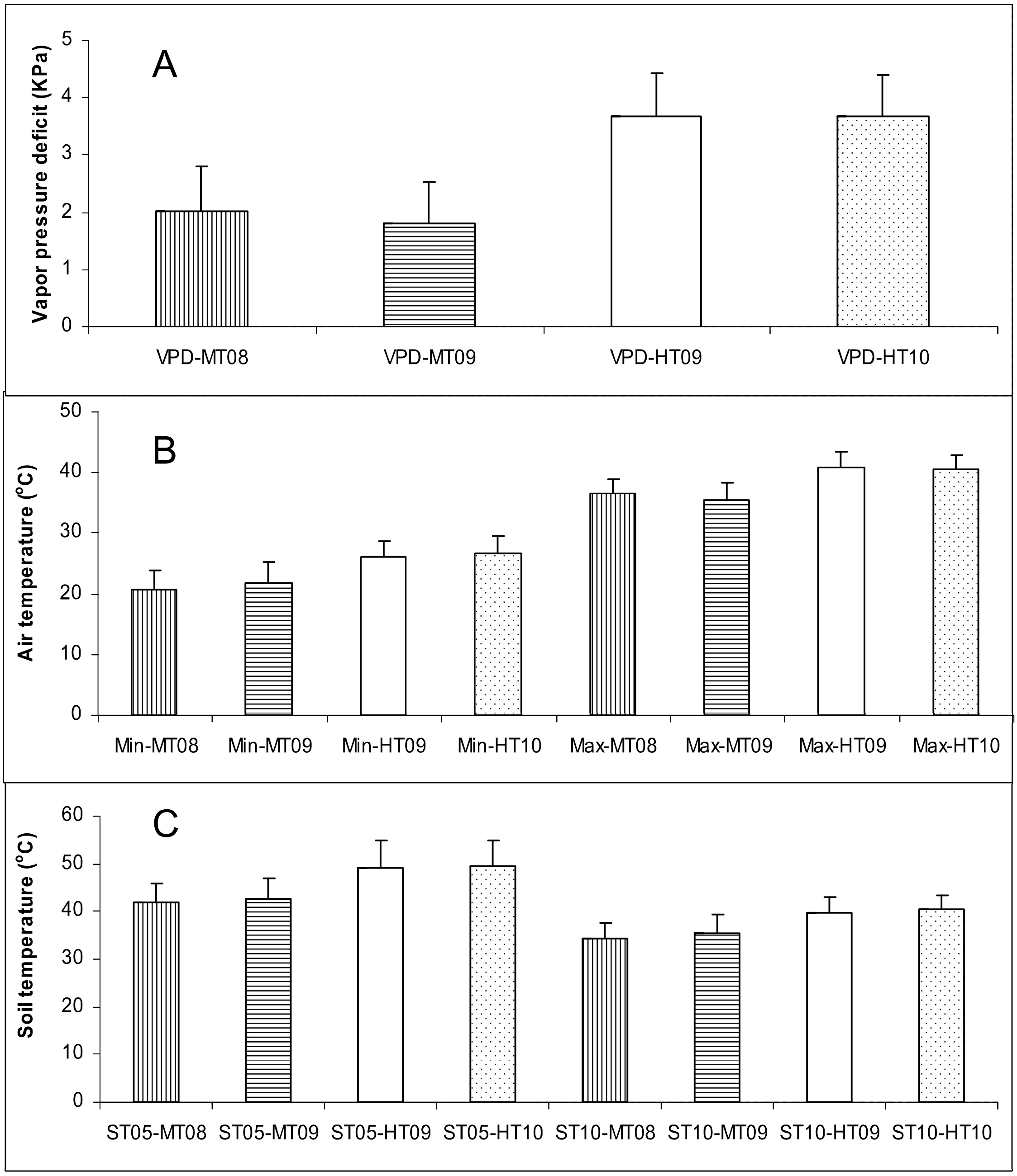

Figure 1 : Climatic data on field trials conducted in late planting (2008 (MT08) ; 2009 (MT09)) and summer (2009 (HT09) ; 2010 (HT10)) at Sadore.

Données climatiques des essais en champ conduits en fin saison hivernale (2008 (MT08) ; 2009 (MT09)) et en contre saison (2009 (HT09) ; 2010 (HT10)) à Sadore.

Legend : VPD = vapor pressure deficit (A), Max = maximum (B), Min = minimum (B), ST05 and ST10 = soil temperature at 5 cm and 10 cm (C) MT = moderate temperature, HT = high temperature,

VPD = déficit de pression de vapeur (A) ; Max = température maximale de l'air (B) ; Min = température minimale de l'air (B) ; ST05 et ST10 = température du sol à 5 cm et 10 cm (C). MT = température modérée, HT = haute température

Table 1 : ANOVA (F value) for pod (Py), haulm (Hy) and Harvest index (HI) at Sadore during summer 2009 (HT09) and 2010 (HT10). Water treatment (Trt) and GxTrt interaction effects.

Analyse de variances de rendement de gousses (Py), rendement de fanes (Hy) et d'indice de récolte (HI) à Sadore durant la contre saison 2009 (HT09) et 2010 (HT10). Effet du traitement hydrique (Trt) et interaction génotype-traitement hydrique (GxTrt).

	Summer 2009 (HT09)				Summer 2010 (HT10)		
	df	Py	Hy	HI	Py	Hy	HI
G	267	3.67	6.28	8.18	3.30	2.58	7
Trt	1	3062	1813	1475	1955	86	1386
GxTrt	-	4.47	7.34	6.31	3.48	4.29	3.79

Legend : G = genotype ; Trt = water treatment ; Df = degree of freedom / *G = genotype ; Trt = Traitement hydrique ; DF = degré de liberté.* F value > 1.96 = significant at 0.05 level

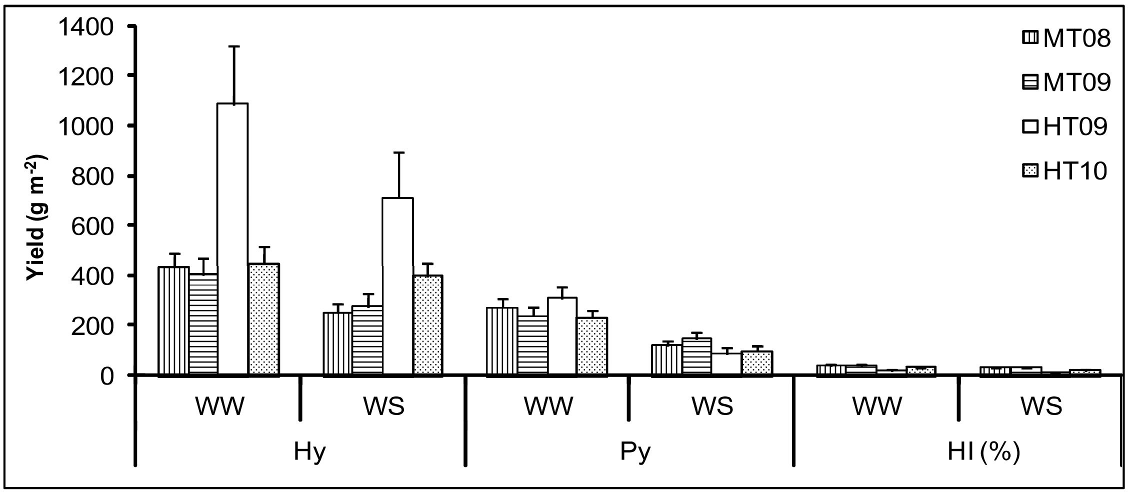

Figure 2 : Means of pod yield (Py), haulm yield (Hy) and harvest index (HI) in field trials MT08, MT09, HT09 and HT10 at Sadore

Rendement moyen de gousses (Py), de fanes (Hy) et indice de récolte (HI) MT08, MT09, HT09 et HT10 à Sadore.

Table 2 : Pod yield (Py), haulm yield (Hy) and Harvest index (HI) decrease (%) due to drought stress in moderate (MT08, MT09) and high (HT09, HT10) temperatures conditions.

Baisse (%) de rendement en gousses (Py), rendement en fanes (Hy) et de l'indice de récolte (HI) due au stress hydrique en conditions de températures modérées (MT08, MT09) et hautes (HT09, HT10).

	Py (%)	Hy (%)	HI (%)
MT08	55	42	25
MT09	38	31	25
HT09	72	34	50
HT10	59	11	33

Table 3 : ANOVA (F value) for pod yeild, haulm yield and Harvest index under WW and WS conditions during late planting 2008 and 2009, and summer 2009 and 2010. Environment and GxE interaction effects.

Analyse de variances de rendement gousses (Py), rendement de fanes (Hy) et indice de recolte (HI) sous traitement bien irrigue (WW) et stresse (WS) en fin saison hivernale 2008 et 2009 et en contre saison 2009 et 2010. Effect de l'environement (E) et interaction génotype-environnement (GxE).

		WW			WS		
	df	Py	Hy	HI	Py	Hy	HI
G	267	2.55	4.43	8.77	3.07	6.68	8.77
E	3	102	756	204	255	353	1191
GxE		7.20	11.33	10.49	7.75	8.77	8.98

F value > 1.96 = significant at 0.05 level

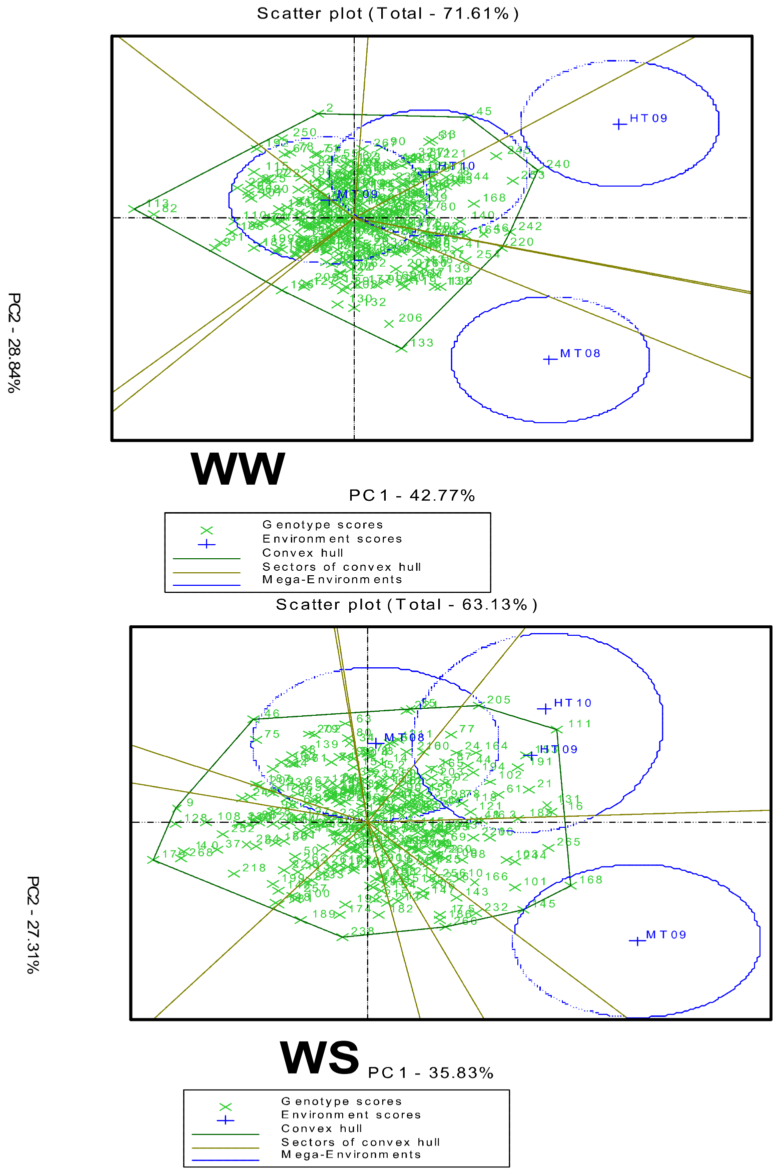

Figure 3 : GGE biplot indicating the existence of mega environment under well-watered (WW) and water stress (WS) conditions in moderate (MT08, MT09) and high (HT09, HT10) temperatures.

Génotype et génotype x environnement (GGE) biplot indiquant l'existence des mega environnements en conditions d'irrigation (ww) et de stress en eau (ws) à température modérée (MT08, MT09) et à température élevée (HT09, TH10).

Table 4 : Ten highest and lowest yielding genotypes under either well-watered (ww, bold) and water stress (ws, bold) conditions during moderate (MT), high (HT) and/or across (MTHT) temperature seasons. For either selection case (WW or WS) pod yield (Py, g m^{-2}) is also given for the other water treatment (WS or WW, normal font). For MT and HT, the means are those of two seasons within each temperature regime and water treatment, whereas for MTHT, the means are those of the four seasons within water treatment. Genotypes labeled with MTHT are those with broad adaptation to different temperature conditions.

Dix génotypes a haut et faible rendements en gousses sous traitement bien irrigue (ww, en gras) et sous stress (ws, en gras) en saisons a températures modérée (MT), élevée (HT), et/ou a travers les saisons (MTHT). Pour les sélections en ww, le poids gousses en ws est indique et vice versa. Pour MT et HT, les valeurs sont les moyennes des 2 saisons pour chaque régime hydrique tandis que pour MTHT, les valeurs sont les moyennes des 4 saisons par régime hydrique. Les génotypes de MTHT sont ceux adaptes aux températures modérée et élevée.

	Highest yielding under WW			Highest yielding under WS			Lowest yielding under WW			Lowest yielding under WS		
Season	Genotypes	Py-ww	Py-ws	Genotypes	Py-ww	Py-ws	Genotypes	Py-ww	Py-ws	Genotypes	Py-ww	Py-ws
MT	ICG 7181	406	116	ICG 5891	244	215	ICG 76	138	92	ICG 188	162	54
MT	ICG 8253	384	150	ICG 6057	245	192	ICG 6667	118	83	ICG 2738	136	66
MT	ICG 8285	434	68	ICG 9777	244	225	ICG 6766	154	88	ICG 4670	193	76
MT	ICG 8490	404	152	ICG 9809	208	130	ICG 12921	129	106	ICG 8083	182	64
MT	ICG 8517	477	139	ICG 11109	269	197	ICGV 02148	124	108	ICG15390	164	83
MT	ICG 8751	433	158	ICG 11542	354	218	ICG 7897	135	52	ICG 6667	59	42
MT	ICG 9315	412	147	ICG 12625	244	211	ICG 11426	120	37	ICG 6643	102	37
MT	ICG 13982	442	119	ICG 15386	368	218	ICG 6643	102	37	ICG 11426	120	37
MT	ICG 14985	417	52	J 11	224	203	ICG 4746	77	51	ICG 15419	163	35
MT	ICGV 02271	409	125	ICGV 97183	375	227	ICG 4906	69	34	ICG 4906	69	34
HT	ICG 1668	464	98	ICG 862	245	181	ICG 188	181	53	ICG 9905	134	52
HT	ICGVSM99507	506	103	ICG 8285	280	181	ICG 1534	185	89	ICG 11862	178	65
HT	ICG 2925	442	105	ICG 1703	265	142	ICG 4906	116	67	ICG 12189	152	90
HT	ICG 5236	384	120	ICG 4729	249	144	ICG 6667	104	83	ICG 12682	187	104
HT	ICG 11219	441	109	ICGVSM99504	279	154	ICG 7963	184	63	ICG 1823	147	78
HT	ICG 15042	430	134	ICG 10053	243	173	ICG 4746	153	71	ICG 11426	148	30
HT	ICG 15403	559	104	ICG 12991	316	171	ICG 11426	148	30	ICG 6643	95	27
HT	ICGV 02266	493	85	ICG 12879	193	181	ICG 15419	128	65	ICG 12235	194	26
HT	ICGV 98294	398	134	ICG-13943	247	130	ICG 7897	104	45	ICG 4906	58	19
HT	ICG 1668	464	98	ICG 15042	286	135	ICG 6643	95	27	ICG 6667	52	17
MTHT	ICG 2738	295	117	ICG 862	265	140	ICG 6022	150	68	ICG 8083	249	60
MTHT	ICG 9362	313	90	ICG 6022	300	118	ICG 15419	146	50	ICG 188	160	58
MTHT	ICG 11088	283	153	ICG 6646	277	142	ICG 6646	139	89	ICG 15419	146	50
MTHT	ICG 11219	323	176	ICG 6813	273	157	ICG 11426	134	33	ICG 6766	102	50
MTHT	ICG 14985	315	109	ICG 8285	311	124	ICG 7897	119	49	ICG 11862	257	49
MTHT	ICG 15403	327	120	ICG 10053	302	167	ICG 4746	115	61	ICG 7897	119	49
MTHT	ICG 15415	342	115	55-437	313	161	ICG 6766	102	29	ICG 11426	134	33
MTHT	J 11	312	150	ICG 10950	319	149	ICG 6643	98	32	ICG 6643	98	32
MTHT	ICGV 01232	329	136	ICG 12509	274	155	ICG 4906	63	26	ICG 6667	55	29
MTHT	ICGV 02266	344	112	ICG 12879	267	168	ICG 6667	55	50	ICG 4906	63	26

CORRELATIONS BETWEEN POD YIELD AND POSSIBLE TRAITS

Among the all traits measured during the four experiments only the partition rate (P) showed significant correlation with pod yield under both WW [MT08 ($r^2 = 0.17$), HT09 ($r^2 = 0.25$), MT09 ($r^2 = 0.18$) and HT10 (r2 = 0.22)] , and WS [MT08 ($r^2 = 0.47$), HT09 ($r^2 = 0.19$), MT09 ($r^2 = 0.16$) and HT10 ($r^2 = 0.21$)] conditions.

DISCUSSION

Wide variation was observed in this study for pod yield, haulm yield and harvest index under control (WW) and drought (WS) conditions across seasons. Similar results were obtained by Rebetzke *et al.* (2004) and Singh *et al.* (2008).

The negative effect of drought stress on pod yield was higher under high temperature seasons (72 %) than under moderate temperature seasons (55 %). These results indicated that the intermittent drought stress had a more severe effect on pod yield during the high temperature than during the moderate temperature seasons, which likely relates to the higher temperatures of the high temperature seasons. Authors found previously a depressive effect of drought and heat stress on groundnut pod yield (Ntare and Williams, 1998 ; Mekontchou1 *et al.,* 2006 ; Girdthai *et al.,* 2010 ; Mothilal *et al.,* 2010). The HI decrease and the haulm yield increase observed in high temperature under WW conditions suggest an effect of the high temperature on the reproductive processes, but not on plant growth. The differences in pod yield between moderate temperature and high temperature seasons are then explained by a higher growth in the high temperature, in part explained by the longer season duration, than in the moderate temperature season. Indeed, the experiments lasted 130 days in high temperature season compared to 120 days in moderate temperature season. Also, the differences in VPD between the seasons could have played a major role. Indeed, differences in the sensitivity of transpiration to the vapor pressure deficit have been found in groundnut (Devi *et al.,* 2010). Then under high temperature combined with drought stress, the effect of heat on the reproductive processes is reinforced. Thus, in additions to drought effect, high temperature affecting the reproductive process could explain the greater depressive effect observed on pod yield and harvest index in the high temperature season compare to the moderate temperature season. Previous works reported that reproductive processes in groundnut are sensitive to temperature. It was found that increasing air and soil temperatures reduced fruit set, pods number and yield in groundnut (Vara Prasad *et al.,* 2000 ; Craufurd *et al.,* 2000 ; Craufurd *et al.,* 2003). In addition, Ntare *et al.* (2001) showed that pod yield of groundnut genotypes declined by more than 50 % when flowering and pod formation occurred when maximum temperatures averaged 40 °C. Our results showed a difference of partition rate between high temperature and moderate temperature season. The highest partition rate (results not shown) was observed under moderate temperature seasons compared to high temperature season under both WW and WS conditions. The effect of high temperature stress on pod formation during high temperature can explain part of these differences. In addition, high temperature stress could decrease the partition rate. Songsri *et al.* (2008) reported that the ability to partition dry matter into harvestable yields under limited water supply is an important trait for drought tolerant genotypes. In this study, genotypic and genotype by water treatment interaction (GxTrt) were both significant and had similar magnitude for both moderate temperature and high temperature seasons 2009 and 2010, indicating the need to select genotypes under each respective water treatment. The magnitude of GxE therefore suggests that the selection for best genotypes is specific to the screening environment, which was confirmed by GGE biplots, used to analyze GxE interactions. The mega environments observed under both WW and WS conditions revealed that genotypes behaved differently across environments. This indicates that, in each water regimes the highest yielding genotype in the moderate temperature season differed from those in the high temperature season. These contrasting materials could be used in breeding program to develop cultivars targeted to environments with differing temperatures. Additionally, the results on the response to drought and/or heat stress of these genotypes notably under control conditions will contribute to understand the difference of involved mechanisms. It has been reported that highest yielding genotypes are those with high yield in different environments and producing consistently from year to year

(Reza *et al.,* 2010 ; Finlay and Wilkinson, 1963). Using GGE biplot, the broad adapted genotypes across year and temperature for each of WW and WS treatments were selected. These genotypes, provided in Table 4, could be considered as having the most «stable» yields across seasons. Thus, according to the target environment (moderate or high temperature), the water treatment (WW, WS) and, the yield and stability, different genotypes could be recommended. Base on the correlation with pod yield, partition rate could be used as selection criteria for improving intermittent drought and heat tolerance in groundnut.

CONCLUSION

Drought stress decreased groundnut pod yield and its component but the effect was greater when it was combined with heat stress. Indeed, high temperature affects the reproductive processes, both under WW and WS conditions, whereas growth processes were not affected in the high temperature season. The existence of significant GxE for pod yield revealed different genotypic responses to drought and heat stress across environments. In additions to genotypes specifically adapted, several broadly adapted genotypes were identified. Further investigations in field and/or control conditions are needed to identify more relevant traits putatively related to combined drought and heat stress.

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