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Full Length Research Paper

Variation and association among characters genetically related to yield and yield stability in *Coffea canephora* genotypes

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Water deficit stress is a main factor determining yield and yield stability in Robusta coffee (*Coffea canephora* P.). Studies were conducted to identify agronomic traits that offer genetic sources of drought tolerance associated with yields and yield stability. In a nine-year experiment, 18 genotypes were assessed for mean value and variation in three diverse environments, for nine vegetative traits, five reproductive traits and bean yield. Drought tolerance was expressed by a visual scale of leaf scorching from 0 to 5: tolerant – susceptible on the genotypes in 2000 when there was drought, and genetic associations between leaf scorching and the traits established. Significant interaction (P ≤ 0.05), and location (P ≤ 0.05) effects were observed for leaf scorching scores and all the traits, except stem diameter and diameter of primary branches. Significant (P ≤ 0.05) genotypic effects were also observed for all the traits, except fruits per node. Canopy diameter (Span), number of primary branches per plant (NPB), fruit-set (FS) and bean yield over seven years (MY1-7) were inversely and significantly (P ≤ 0.05) correlated with leaf scorching scores. Span, NPB and FS were also significantly (P ≤ 0.05) correlated with MY1-7. Span was highly correlated with stem diameter, length and diameter of primary branches. Eight genotypes each with high mean performance for (MY1-7) and fruit set (FS), seven for Span, and five for NPB, were among the top 10 genotypes which recorded the lowest leaf scorching scores. The results indicate that, Span and its associated traits, NPB, and FS could be exploited, through indirect selection for superior *Coffea canephora* genotypes, for direct utilisation or for breeding for adaptation to drought-stress.

Key words: Drought tolerance, leaf scorching, agronomic traits, yield, yield stability, genetic correlations, genetic variation, indirect selection, *Coffea canephora*.

INTRODUCTION

Coffea canephora production is confined to the inter-tropical zone, from 20 to 25°N and 24°S, mainly due to ecological factors related to temperature and humidity (Smith, 1989). Within this main production zone, the crop is affected adversely by different abiotic stresses such as extreme temperatures, salinity, fluctuations in incident light and drought (Andrea et al., 2003; DaMatta, 2004c; Partelli et al., 2009; Partelli et al., 2010; Batista-Santos et al., 2011). As drought episodes are much frequent than the other stresses, drought-stress is considered the major environmental factor limiting coffee yield in most coffee growing areas (DaMatta and Ramalho, 2006). The effect on yield depends on the period of drought: before flowering, during fruit-setting, or fruit development. From the standpoint of breeding, the differential responses of genotypes to water-deficit stress have been identified as a main factor contributing to genotype-environment interactions, thus complicating selection for yield (Ehlers, 1994; Bidinger et al., 1996). In coffee, leaf-scorching has been attributed to sensitivity to drought (DaMatta and Rena, 2001; DaMatta, 2004a; DaMatta and Ramalho, 2006), with drought-tolerant cultivars showing delayed leaf wilting and shedding than drought-sensitive ones

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(Orozco and Jaramillo, 1978). Visual scoring method of leaf-scorching has, therefore, been the main selection criterion for drought-tolerant genotypes at the vegetative phase (Cilas et al., 2003). In the absence of water-deficit stress, however, such method cannot be useful.

According to DaMatta and Ramalho (2006), cultivars more tolerant to drought generally differ morphologically and/or physiologically, with mechanisms allowing greater production under restricted water supply. Hence, understanding such mechanisms in genotypes naturally adapted to drought could help improve their agronomic performance. DaMatta (2004b) discusses some physiological mechanisms that have been shown to contribute to yield under drought conditions such as: gas exchange (Meinzer et al., 1992) carbon isotope discrimination (Gutiérrez and Meinzer, 1994), osmotic adjustment (Meinzer et al., 1990; DaMatta et al., 2003), and solute accumulation (Maestri et al., 1995). DaMatta (2004b), however, considered most of these methods not sufficiently convenient or effective mechanism of drought-tolerance in coffee.

Agronomic characteristics of most crops were found to be associated with their tolerance to drought (Zhong-hu and Rajaram, 1994; Omanya et al., 1996; Ehdaie et al., 2001). In coffee, root characteristics such as larger root mass (Ramos and Carvalho, 1977) and deeper root system (Pinheiro et al., 2005) were found to be associated with drought-tolerance. Methods based on root characteristics, however, are either not easy to measure, destructive, or too time consuming for plant breeders to evaluate large segregating populations. Hence, a complementary approach to improve Robusta coffee performance could involve the identification and selection of agronomic/morphological traits associated with tolerance to drought-stress that are relatively easy to measure. Correlation studies of agronomic traits, in this respect, should have the advantage of relying on measurement and count data that do not require sampling of tissue, and hence, non destructive. In coffee, agronomic traits associated with yields have been reported for both *C. canephora* (Leroy et al., 1994; Cilas et al., 2006; Anim-Kwapong and Adomako, 2010) and *C. arabica* (Walyaro and Van der Vossen, 1979; Cilas et al., 1998). However, little information exists on the agronomic traits that offer genetic sources of drought tolerance that are associated with yields and yield stability (Cilas et al., 2003).

The correlation between two traits plays an important role in breeding programmes as improvement of one trait causes simultaneous changes in the other trait (Falconer and Mackay, 1996). Genetic correlation, which is the proportion of variance that two traits share due to genetic causes, is useful in studying the associated genetic relationships among traits under selection. This correlated response among traits, forms the basis of indirect selection; hence, an understanding of the agronomic traits genetically correlated with drought-tolerance at the vegetative and reproductive phases of the plant should provide an opportunity for exploiting such traits, when they occur in the population, for improving coffee yields and yield stability. The objectives of the present study were: (a) To assess variation among Robusta coffee genotypes for visual leaf-scorching, and for vegetative and reproductive traits, including yield. (b) To estimate the magnitude and direction of genetic associations between leaf-scorching and the traits and (c) To select traits that may be associated with tolerance to drought-stress at the vegetative and reproductive stages.

MATERIALS AND METHODS

Genetic material

Twelve clones extracted by individual selection, based on yield, from a population of three half-sib family groups introduced from Cote d`Ivoire, together with six clones introduced from Togo, were used for the study (Table 1).

Experimental sites and design

The study was conducted from 1996 to 2005 at three rain-fed sites at Tafo, Fumso and Bechem, representing a wide range of soil types and climatic regimes within the forest zone of Ghana where coffee is cultivated. The Tafo site is the research farm of the Cocoa Research Institute of Ghana (CRIG) situated at latitude 6° 13' N, longitude 0° 22' W, and altitude 220 m above sea level (asl) in the Eastern region of Ghana. Tafo has a mean total annual rainfall of approximately 1480 mm with a dry season from December to February recording mean monthly rainfall of approximately 44 mm. The soil is sandy loam classified as Haplic Luvisol, brown to yellowish red, well drained, developed *in-situ* from weathered materials of hornblende granodiorite (Adu and Asiamah, 1992)). Fumso (latitude 6° 6' N, longitude 1° 27' W, and altitude 122 m asl) has a total annual rainfall of approximately 1320 mm. The dry season at Fumso from December to February receives a monthly average rainfall of approximately 29 mm. The soils at the site (Fumso Cocoa Station) belong to the Kumasi Series and are classified as Ferric Luxisol, dark reddish brown to reddish brown, well drained and developed over coarsely-quartzose, biotite granodiorite and have a coarse sandy to fine gravelly topsoil (Ahn, 1961). Bechem (latitude 7° 5' N, longitude 2° 2' W, and altitude 259 m asl) is drier, with a mean total annual rainfall of about 1220 mm, and experiences a marked dry season from December to February receiving a monthly average rainfall of about 17 mm. The soils at the site belong to the Bechem series and of sedentary Forest Ochrosol-Rubrisol intergrades developed over non-micaceous hornblende granite. The topsoil is a dark brown, humus fine sandy loam to light clay, crumbly, loose and porous. It absorbs rainfall readily but liable to dry out during prolonged dry spell (Ahn, 1961). Mean average daily temperatures are about 26.8, 27.0 and 26.2°C for Tafo, Fumso and Bechem, respectively.

Single-node cuttings of the clones used were rooted in propagators and cultured in nursery bags for six months. Thirty-two plants of each genotype were randomly assigned to each of the three environments. At each location, planting was done using a randomized complete block experimental design with four replications. Each plot, measuring 2.44 x 19.51 m, comprised of a single row of eight coffee trees of each genotype. Both inter-row and inter-plant spacings were 2.44 m giving a density of 1680 plants per hectare. *Gliricidia sepium* shade trees were planted in rows at 4.9 m spacing between each other in the trial plot. Planting at all three environments was done in June 1996. No fertilizer was

Table 1. Planting material and their sources of origin.

Clones from Cote d` Ivoire[†]	Clones from Togo[††]
A129	197
A115	149
A101	126
B170	181
B96	375
B36	107
B191	
E174	
E138	
E139	
E90	
E152	

[†]Selection based on 10-year yields. [††]Selection based on 3-year yields.

applied and crop-management practices were similar for all locations. In order to assess genetic differences in number of stems produced, the plants were allowed to grow on one or two stems developed from the single-node cuttings. Stems were capped at 18 months from field planting by removal of the terminal bud and subsequently capped to 1.8 m and maintained at that height. The first capping resulted in each main stem developing into two branches at the point of capping.

Data collected

Measurements of vegetative characteristics were taken three months after field planting on diameter of the main stem (girth), crown diameter (span) and number of primary branches, and repeated each year after field planting until the plants were 48 months in the field. Vegetative measurements taken when the plants were 48 months in the field, at the stage of maximum expansion, were used for this study. Four plants were randomly selected from each genotype per plot for assessment. Traits assessed included girth (taken at 10cm above the ground in mm), span (cm) taken as the width of the canopy measured at the widest portion of the tree canopy, number of stems, total number of primary branches counted per plant and per stem, and total number of secondary branches per plant. Length of primary branches (measured from the point of attachment to the main stem to the apex in cm), diameter of primary branches (10 cm from the main stem in mm) and number of nodes per primary branch were estimated as an average value of the six longest branches at the middle of the stem per plant. Where there were more than one stem, stem diameter was calculated according to Stewart and Salazar (1992), and span was taken for only the biggest stem.

At flowering and fruiting time in December 1998 to May 1999, two plants from each plot were randomly tagged. Three flowering primary branches at the middle of each plant were tagged for the determination of the number of flowering nodes per branch and number of flowers per node. Fruits that remained on the branches at six months from initial flowering were counted and used in estimating the number of fruiting nodes and fruits per node. Percent fruit-set (fruit-set) was estimated as the proportion of total flowers counted on the three flowering branches per tree that set fruit and remained on the branches at six months from flowering. Data recording was repeated the following season (December 1999 to May 2000), when there was severe drought at all three locations using three plants per plot, and data averaged across plots for the two seasons.

Assessment of plants for drought tolerance was done in February 2000 when coffee leaves appeared scorched due to severe moisture stress at all three sites. Leaf scoring of the plants was done based on dry leaves on a scale of 0 (no dry leaves) to 5 (virtually all dry leaves): drought resistant/tolerant – susceptible on all plants at all three sites. Yield was recorded on each tree for seven production years from Oct. to Jan. each year for the period 1998/1999 to 2004/2005. Transformation of cherry weight to average clean coffee yield per ha/yr was done for each of seven competitive stands per plot using the formula: wet cherry weight per stand (kg) x number of trees per ha x outturn. Outturn was estimated for each genotype as an average of weight of dry beans divided by weight of wet berries.

Statistical analysis

Analyses of variance and covariance were performed on the data using Minitab statistical software (MINITAB, 1997) to examine the presence of statistically significant differences among genotypes, locations and their interactions for these characters. The standard error of difference between means (SED) was estimated to identify genotypes that were significantly different from each other for the traits. The statistical model used for the combined analyses was:

$$Y_{ijk} = \mu + g_i + e_j + (ge)_{ij} + R_{jk} + \varepsilon_{ijk}$$

Where Y_{ijk} is the k^{th} observation of any variable in the r^{th} replications in environment j on genotype i; μ the general mean; g_i and e_j represent the effects of the i^{th} genotype and the j^{th} environment; $(ge)_{ij}$ is the interaction effect between the genotypes and the environment; R_{jk} is the effect of the k-th replication within the j-th location, ε_{ijk} is the random error associated with the k^{th} observation on genotype i in environment j. i = 18; j = 3; r = 4. The effects g_i`s, ej`s, $(ge)_{ij}$`s and $\varepsilon_{ijk}$`s are assumed independently and randomly distributed with zero means and variances σ^2_g, σ^2_l, σ^2_{gl} and σ^2_e respectively. The form of the analysis of variance and covariance with expectations of mean squares and cross products is presented in Table 2. Genotypic correlations (R_G) among the agronomic traits were computed from the variances and covariances as:

$$R_G = \mathrm{COV}_{G(XY)} / \sqrt{\sigma^2_{G(X)} \sigma^2_{G(Y)}}$$

Table 2. Form and generalized expectations of analysis of variance and covariance for two characters X and Y.

Source of Variation	Degrees of freedom[‡]	Mean square	Analysis ofvariance (*X*)	Analysis of variance (*Y*)	Analysis of covariance (*XY*)
Reps/locations	(r-1)L				
Locations (Loc)	L-1	M_l			
Genotypes(Gen)	N-1	M_g	$\sigma^2{}_{e(X)}+r\sigma^2{}_{gl(X)}+r\,L(\sigma^2{}_{g(X)})$	$\sigma^2{}_{e(Y)}+r\sigma^2{}_{gl(Y)}+rL(\sigma^2{}_{g(Y)})$	$\sigma_{e(XY)}+r\sigma_{gl(XY)}+rL(\sigma_{g(XY)})$
Gen x Loc	(N-1)(L-1)	M_i	$\sigma^2{}_{e(X)}+r\sigma^2{}_{gl(X)}$	$\sigma^2{}_{e(Y)}+r\sigma^2{}_{gl(Y)}$	$\sigma_{e(XY)}+r\sigma_{gl(XY)}$
Error	(N-1) (r-1)L	M_e	$\sigma^2{}_{e(X)}$	$\sigma^2{}_{e(Y)}$	$\sigma_{e(XY)}$

[‡] *r* = number of replications = 4; L = number of locations = 3; N = number of genotypes =18.

Table 3. Range and variance components of vegetative traits related to drought tolerance in 18 genotypes of Robusta coffee in three locations.

Traits	Range		Mean	Mean square values			
	Genotype	Location		Genotype	Location	Gen. x Loc.	Error
Girth (mm)	52 -76	63-66	64	493.4***	128.0	39.1	31.9
Span (cm)	190-229	206-217	210	1231.7***	2506.1*	226.7*	132.7
Length of prim. branch (cm)	108-132	111-121	117	650.53***	1701.62*	108.17***	47.69
Diam. of prim. branch (mm)	6.7-8.6	7.6-7.9	7.7	3.93***	1.96	0.20	0.18
No. of nodes/prim. branch	18.5-22.3	20.2-21.1	20.5	19.06***	15.05	3.76***	1.83
No. Stems/ plant	1.08-1.65	1.33-1.41	1.35	0.4118***	0.2613	0.0946*	0.0573
No. prim. branches /stem	84-125	73 – 145	103	1379.1*	102740.7***	663.1***	256
No. prim. branches /plant	105-157	97-186	132	2590.3*	164751.6***	1399***	570.4
No. Sec. branches /plant	7 – 55	17 – 28	22	1871.7***	2394.8*	348.1***	151.4
Leaf- scorching	1.02 - 2.92	1.64 - 2.35	1.99	2.76***	8.96***	0.90***	0.28
				df =17	df =2	df =34	df =153

* = p <0.05, ** = p < 0.01, *** = p < 0.001.

Where $COV_{G(XY)}$ is the estimated genotypic covariance component for traits X and Y, $\sigma^2{}_{G(X)}$ and $\sigma^2{}_{G(Y)}$ are the genotypic variance components respectively for traits X and Y (Falconer and Mackay, 1996). For correlations involving drought assessment scores, low vales for leaf scorching scores correspond to increased scores for drought tolerance. Test for significance of the correlations was by standard procedure (Steel et al., 1997).

RESULTS

Variance components

The analysis of variance revealed significant ($P \le 0.05$) interactions between the genotypes and the locations for leaf scorching and for all the vegetative traits except girth and diameter of primary branches. Highly significant ($P \le 0.001$) genotypic differences were also observed for leaf scorching and the vegetative traits except number of primary branches per plant and per stem, which showed lower variation ($P \le 0.05$). These observations indicate the presence of substantial variability among the tested genotypes (Table 3), and the possibility of selection for high performing genotypes for these traits. Genotypes with high values for span, girth, as well as length, number and diameter of primary branches had relatively lower leaf scorching compared with genotypes with less vigorous growth habits (Table 4). The lowest average leaf - scorching per tree was recorded from genotypes E90, E139, E138 and 149 compared to all other genotypes except B36, B96, 197 and E174. The locations vary significantly ($P \le 0.001$) for number of primary branches per plant and per stem, and for leaf scorching. Bechem had the highest leaf-scorching score with plants with relatively fewer numbers of primary branches the most affected. The locations also vary significantly ($P \le 0.05$) for span, length of primary branches and number of secondary branches. There were, however, no differences among the locations for girth, diameter and number of nodes of primary branches, and number of stems per plant.

Analysis of variance showed significant interactions ($P \le 0.001$) between the genotypes and the locations for all the reproductive traits observed, except number of

Table 4. Mean trait scores of vegetative traits related to drought tolerance in 18 genotypes of Robusta coffee in three locations.

Genotypes/ Locations	Girth (mm)	Span (cm)	Length of prim. branch (cm)	Diam. of prim. branch (mm)	No. nodes /prim. branch	No. stems /plant	No. prim branches/ stem	No. prim. branches /plant	No. sec. branches/ plant	Leaf scorching
Genotypes										
E138	76.4	219.4	119.9	8.2	21.9	1.2	119	139	7	1.31
E90	71.0	228.6	129.3	8.2	20.3	1.4	107	135	17	1.02
E139	65.0	216.0	119.1	7.9	20.9	1.6	100	152	20	1.15
E152	64.7	222.3	123.2	8.6	22.1	1.3	110	135	24	2.04
126	64.8	210.7	108.1	7.5	19.8	1.5	98	133	33	2.92
149	67.3	204.2	109.5	7.8	18.5	1.7	94	151	55	1.56
B36	64.7	219.9	132.3	7.4	20.9	1.4	97	136	16	1.85
197	58.5	196.9	108.7	6.9	19.7	1.5	114	157	14	1.98
B96	72.3	211.8	120.9	7.9	20.0	1.6	95	145	21	1.95
E174	66.0	221.2	118.2	8.2	21.8	1.2	101	113	8	1.98
A129	67.4	210.9	113.7	8.4	19.2	1.3	102	124	20	2.50
107	56.6	208.6	122.1	7.0	21.9	1.0	125	137	17	2.00
B191	52.7	195.7	112.3	6.7	18.5	1.3	91	111	32	2.33
181	66.3	203.6	107.9	7.6	21.2	1.7	84	133	10	2.40
A101	64.2	210.4	116.9	8.0	20.2	1.3	97	119	16	2.31
A115	58.0	210.9	116.2	7.8	22.3	1.2	93	105	15	2.19
B170	52.3	189.5	108.4	6.7	21.7	1.1	113	122	45	2.13
375	66.8	205.3	109.7	7.2	18.8	1.2	113	123	18	2.15
SED (153df)	2.3	4.7	2.8	0.2	0.6	0.1	7	10	5	0.22
Locations										
Bechem	63.7	216.9	121.0	7.9	21.1	1.4	73	97	28	2.35
Fumso	63.2	205.6	111.4	7.6	20.2	1.3	91	112	20	1.64
Tafo	65.7	208.4	117.0	7.6	20.3	1.3	145	186	17	1.97
SED (153df)	Ns	1.9	1.2	Ns	Ns	Ns	3	4	2	0.09

Table 5. Range and variance components of reproductive traits related to drought tolerance in 18 genotypes of Robusta coffee in three locations.

Traits	Range		Mean	Mean square values			
	Genotype	Location		Genotype	Location	Gen x Loc	Error
Fruit-set (%)	32.3-51.3	22.0-54.3	42.2	404.4***	22185.2***	98.3***	25.3
Number of fruits/node	12.7-17.6	10.6-18.6	15.6	28.1	1354.9***	17.3***	4.7
Number of fruiting nodes	8.7-11.3	6.2-12.3	10.2	8.8***	857.6***	3.0***	1.1
Number of flowers/node	28.7-41.8	31.7-39.0	35.2	155.0***	955.4***	17.3***	7.8
Number of flowering nodes	10.8-13.7	11.0-13.2	12.2	7.3***	88.9***	1.2	0.8
First 1- 3 years yield (kg/ha/yr.)	853-1635	445-1768	1324	512929***	41634417***	164807***	65813
Last 4-7 years yield (kg/ha/yr.)	1063-2582	1079-2451	1838	2278848***	35027941***	372520***	148158
Overall seven years yield (kg/ha/yr.)	1015-2178	808-2152	1625	1242185***	37096509***	194560***	76828
				df =17	df =2	df =34	df =153

* Significant at P = 0.05. ** Significant at P = 0.01, *** Significant at P = 0.001.

flowering nodes. Highly significant ($P \leq 0.001$) differences among genotypes and locations were observed for all the traits, with the exception of fruits per node, for which the genotypes did not vary. There is, therefore, a substantial variability among tested genotypes and locations for these traits (Table 5). Genotypes with the lowest leaf-scorching score per tree generally also had the best average scores for fruit-set and yields (Table 6). Similarly, Bechem with the highest leaf- scorching score compared with Fumso and Tafo had

Table 6. Mean trait score of reproductive traits related to drought tolerance in 18 genotypes of Robusta coffee in three locations.

Genotypes/ Locations	Fruit-set (%)	No. fruits/ node	No. fruiting nodes	No. flowers/ node	No. flowering nodes	First 3-years yield (kg/ha/yr.)	Last 4-7 years yield (kg/ha/yr.)	Overall seven years yield (kg/ha/yr)
Genotypes								
E138	48.8	15.9	10.9	31.4	12.3	1618	2582	2178
E90	46.4	17.2	10.7	34.9	12.7	1635	2437	2109
E139	50.2	17.3	10.5	33.8	12.1	1629	2422	2073
E152	47.1	15.8	11.5	33.0	13.1	1610	2062	1876
126	43.0	13.3	9.2	28.7	12.0	1276	2235	1801
149	37.8	17.0	8.7	41.8	10.8	1444	1934	1786
B36	32.3	12.7	9.7	35.6	12.4	1283	2076	1772
197	48.9	17.6	10.7	34.9	11.6	1446	1827	1727
B96	44.9	15.3	10.2	31.4	12.4	1092	2060	1603
E174	51.3	17.0	11.3	31.6	12.7	1284	1833	1589
A129	40.6	17.1	9.3	40.0	11.4	1239	1862	1585
107	37.8	13.4	10.6	32.8	13.0	1230	1617	1460
B191	42.7	15.7	9.2	35.5	11.6	1287	1481	1404
181	35.6	15.3	9.6	40.0	11.5	1236	1556	1404
A101	38.8	16.3	10.2	39.9	12.2	1240	1480	1366
A115	34.9	13.5	11.0	35.6	13.4	1227	1443	1354
B170	35.9	15.4	11.1	38.5	13.7	1194	1123	1148
375	41.8	14.9	9.1	35.0	11.3	857	1063	1015
SED (153df)	2.05	Ns	0.42	1.14	0.36	104.7	157.1	113.2
Locations								
Bechem	22.0	10.6	6.2	39.0	11.0	445	1079	808
Fumso	50.1	18.6	12.4	35.1	13.2	1768	1986	1915
Tafo	54.3	17.5	12.0	31.7	12.5	1757	2451	2152
SED (153df)	0.84	0.36	0.17	0.47	0.15	42.8	64.2	46.2

the lowest average fruit-set, number of fruits per node and yields.

Substantial variability among genotypes and environments was also revealed by the wide range between the minimum and maximum values scored for the traits (Tables 3 and 5). For example, average leaf-scorching scores per tree ranged from 1.06 to 2.92 and span from 190 to 229 cm among the genotypes. Fruit-set also varied from 32.3 to 51.3% and average seven years yield from 1 015 to 2 178 kg/ha among the genotypes. Among the locations, drought reaction scores per tree varied from 1.64 to 2.35 and span from 206 to 217 cm. Fruit-set and average seven years yield also ranged from 22.0 to 54.3% and 808 to 2152 kg/ha, respectively. Genotypes with maximum values for the traits associated inversely with leaf scorching may, therefore, be utilised in the breeding programme for the improvement of Robusta coffee for adaptation to drought-stress.

Locations with minimum and maximum values for the traits associated inversely with leaf-scorching can also be noted as drought-stress and non-stress environments for testing genotypes for specific or broad adaptation to drought-stress.

Genetic correlations

Associations among leaf scorching and the vegetative traits are shown in Table 7. Almost all the vegetative traits studied were inversely correlated with leaf-scorching scores, except number of secondary branches, which was positively associated. Good prediction of leaf-scorching was by span $(R_G = -0.53;\ P \leq 0.05)$ and number of primary branches per plant. $(R_G = -0.47;\ P \leq 0.05)$. Good prediction of average seven years yields was also by span $(R_G = 0.65;\ P \leq 0.01)$ and number of primary branches per plant $(R_G = 0.56;\ P \leq 0.05)$. Average seven years yield was also significantly correlated with girth and diameter of primary branches $(R_G = 0.52 - 0.55;\ P \leq 0.05)$. Span, however, showed highly significant genetic associations with girth, length and diameter of primary branches

Table 7. Genotypic correlation coefficients of leaf-scorching with vegetative traits and yield among 18 Robusta coffee clones in three environments.

S/N	Traits	1	2	3	4	5	6	7	8	9	10
1	Leaf-scorching	-									
2	Girth	-0.39									
3	Span	-0.53*	0.67**								
4	Length/prim. branch	-0.45	0.32	0.78***							
5	Diameter/prim. branch	-0.22	0.70***	0.77***	0.38						
6	No.nodes/prim. branch	-0.17	-0.05	0.35	0.39	0.04					
7	Number of stems/ plant	-0.15	0.36	0.00	-0.11	0.08	-0.41				
8	No. prim. branches/ stem	-0.28	-0.05	0.05	0.17	-0.15	0.28	-0.55*			
9	No. prim. branches/plant	-0.47*	0.35	0.08	0.09	0.01	-0.14	0.67**	0.22		
10	No. Sec. branches/ plant	0.11	-0.32	-0.48*	-0.39	-0.30	-0.43	0.18	-0.12	0.11	
11	Overall seven years yield	-0.64**	0.55*	0.65**	0.49*	0.52*	0.13	0.38	0.10	0.56*	-0.12

* Significant at P = 0.05. ** Significant at P = 0.01, *** Significant at P = 0.001.

Table 8. Genotypic correlations coefficients of leaf-scorching with yield and its components among 18 Robusta coffee clones in three environments.

S/N	Traits	1	2	3	4	5	6	7	8
1	Leaf –scorching	-							
2	Fruit-set	-0.52*							
3	Number of fruits /node	-0.49*	0.62**						
4	Number of fruiting nodes	-0.37	0.39	0.15					
5	Number of flowers/node	0.14	-0.56*	0.28	0.36				
6	Number of flowering nodes	-0.08	-0.05	-0.33	0.81***	-0.35			
7	First three years yield	-0.63**	0.48*	0.45	0.39	-0.13	0.11		
8	Last 4-7 years yield	-0.57**	0.53*	0.22	0.14	-0.45	-0.04	0.76***	
9	Overall seven years yield	-0.64**	0.54*	0.31	0.20	-0.36	-0.03	0.89***	0.98***

* Significant at P = 0.05. ** Significant at P = 0.01, *** Significant at P = 0.001.

$(RG = 0.67 - 0.78; P \le 0.01)$, but recorded significantly negative genetic correlation $(RG = -0.48; P \le 0.05)$ with number of secondary branches, a trait which was directly associated with leaf-scorching.

Among the reproductive traits (Table 8), good prediction of leaf-scorching was by fruit-set $(RG = -0.52; P \le 0.005)$, fruits per node $(RG = -0.49; P \le 0.05)$, and yield itself (first three years yield $(RG = -0.63; P \le 0.01)$, last 4 to 7 years yield $(RG = -0.57; P \le 0.01)$ and overall seven years $(RG = -0.64; P \le 0.01)$. Strong positive relationships were observed between fruit-set and yields.

DISCUSSION

In coffee, Orozco and Jaramillo (1978) reported that, drought tolerant cultivars showed delayed leaf wilting and shedding compared with drought sensitive ones. DaMatta and Rena (2001) also observed that, leaf senescence is a consequence of drought, in response to low plant water potential, and argued that leaf senescence in coffee is rather not a result of a survival mechanism to limit transpiration, as observed in some plants. Leaf senescence was, therefore, a reliable parameter for scoring the plants for drought tolerance.

The results showed that, plants with wide span recorded relatively lower leaf-scorching. But wide span is genetically strongly associated with girth, length and diameter of primary branches. Plants with wide span, therefore, had strong main stems and generally long and erect primary branches, implying that plants that showed lower leaf-scorching were more vigorous and larger than those that had higher rate of leaf-wilting in response to drought-stress. Such plants were likely to have more stored assimilates or stem reserves than the smaller plants. In general, plants with large span had higher fruit set, suggesting that, the likely higher stem reserves of these plants play a role in fruit-set of coffee under drought-stress. Stem reserves have been shown to play an important role as source of assimilate (translocated to other parts of the plant) during water-deficit stress in many plant studies (Bonnet and Incoll, 1992; Ehdaie and Waines, 1996; Blum et al., 1997; Ehdaie et al., 2006). Span and its associated traits could, therefore, be exploited for adaptation to drought-stress.

The significant negative genetic association of number of primary branches per plant with leaf-scorching also indicate the sensitivity of the primary branches to drought-stress. This is evident by the significantly lower values for number of primary branches recorded at Bechem, which experienced drier conditions during the study, than at Tafo. The reduced number of primary branches in genotypes with higher leaf-scorching scores as well as under drought-stress conditions at Bechem were likely to be a consequence of senescence of the leaves resulting in the death of the primary branches. The consequent smaller leaf area should lead to lower rate of carbon assimilation, which seemed to be more directly responsible for the decreased crop yield. Meinzer et al. (1992) observed that drought-sensitive coffee plants as well as drought-stressed plants, in addition to showing higher leaf-wilting and shedding, also have fewer and considerable smaller leaves than drought-tolerant plants. Barros et al. (1999) and DaMatta (2004a, b) associated die-back of the primary branches with soil and atmospheric water-deficit, high temperature and their combined effects. Rena and DaMatta (2002) reported die-back of the primary branches to be preceded by death of a large proportion of absorbing root following wilting of the leaves caused by water-deficit stress. This observation the authors argued, could affect yields negatively due to reduced assimilate production. Number of primary branches per plant can, therefore, be used to screen genotypes under drought-stress.

The very high negative genetic correlations observed in this study between leaf-scorching and fruit-set and yield (both at the early and late fruiting stages) show that fruit-set and cherry development of coffee plants are the reproductive traits most sensitive to moisture stress. Flowering of Robusta coffee in Ghana during the study period mostly coincided with the beginning of the dry season, in December, and lasted for about three months. In this study, mean total annual rainfall during the study period varied among the locations from 1220 mm at Bechem, 1320 mm at Fumso, to 1480 mm at Tafo. The effect of drought stress on coffee yield may, therefore, not be due to limiting total moisture availability during the growing period but particularly during the fruit-setting periods, or post-flowering drought stress. This stress was more severe at Bechem which recorded mean monthly rainfall of 17.4 mm during the dry season compared to 43.5 mm at Tafo over the same period. Hence, yields were lowest at Bechem and highest at Tafo. The coffee tree sheds a large number of pin-head berries in the first three months after flowering. Barros et al. (1999) attributed the fruit drop during the first month after flowering to fertilisation failure and that of the second to third months to low carbohydrate supply and water deficit. In this study, up to 78% of flowers failed to develop into fruits at Bechem compared to 46% at Tafo, reflecting the relatively poorer yields recorded at Bechem than at Tafo. The differential ability of the genotypes to mobilise and translocate stem reserves to fruits could have resulted in the differences observed in fruit-set and yield among the genotypes. Wide ranges of physiological (Silva Ramos and Carvalho, 1997; DaMatta et al., 2003; Pinheiro et al., 2005) and biochemical (Lima et al., 2002; Pinheiro et al., 2004; Praxedes et al., 2006) attributes, including high plant water potential, relative water content, deep rooting, maintenance of leaf area, improved tolerance of oxidative stress, and ability for maintaining assimilate export, have been suggested as predictors of drought tolerance in *C. canephora* and *C. arabica.* Some of these attributes could be associated with the agronomic traits that are associated with drought tolerance in this study.

High negative genetic correlations observed between leaf-scorching and yield and the fact that mostly all the traits that confer reduced leaf-scorching also confer higher yields did not only imply that drought is an important environmental stress that determines coffee yields, but that, yield itself can be a criterion for selecting drought-tolerant Robusta coffee plants under stress as discussed for other crops (Mullet and Whitsitt, 1997). The agronomic implications of the association among leaf-scorching scores, early, late and overall seven years yields are that, adaptable genotypes could be selected at the early stages of bearing of the plant as well as from older plants in the later stages of the production cycle. Fruits per node was also inversely associated with leaf-scorching scores, but the comparatively stronger inverse associations between fruit-set and leaf-scorching, and the strong positive association between fruit-set and yields (both at the early and late bearing stages of the plants) clearly show that fruit-set is indeed the most important character, apart from yield, related to reproductive stage drought tolerance in Robusta coffee. From the analyses of variance, significant differences were observed among genotypes in leaf-scorching, span, number of primary branches, yields and fruit-set, implying that selection for good performing genotypes for these characters, which are assessed in a non-destructive manner, will help improve adaptation to drought-stress in this population and in future breeding programmes. Visual scoring of plants using leaf-scorching can only be possible in the presence of moisture stress. Moisture stress may, however, not be present at the juvenile stages of the plant when screening process of genotypes for most traits of agronomic importance may be advantageous for early selection. In this study, however, fruit-set, span and number of primary brabches, the traits most related to reproductive and vegetative stage drought tolerance, and early three-year yields were estimated from data recorded on four to five and half-year old coffee plants under near optimum and moisture stress conditions in three diverse environments. They are, therefore, reliable methods of evaluation in near optimum and stress environments. Our results should, therefore, form an important base for a pre-selection index for high yielding and adaptable coffee genotypes in screening germplasm and segregating generations for characters of agronomic importance for improvement of the crop.

Conclusion

The present study revealed inverse genetic correlations between leaf-scorching and some vegetative and reproductive characters and positive associations among the characters. There was also substantial variation among the tested genotypes for these characters. Span and its associated traits, NPB, and FS could be exploited, through indirect selection for superior *C. canephora* genotypes. Genotypes with desirable high or low average values for these characters should be conserved for direct utilisation or for breeding for genetic improvement of the crop for adaptation to water-deficit stress.

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