Agricultural Sciences, 2021, 12, 1508-1526
https://www.scirp.org/journal/as
ISSN Online: 2156-8561
ISSN Print: 2156-8553

Evaluation of New High-Producing Hybrids of Cocoa Trees in Marginal Crop Areas in Côte d'Ivoire

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How to cite this paper: Kouame, S.T., Tahi, M.G., Sekou, A., Cilas, C. and Akaffou, S.D. (2021) Evaluation of New High-Producing Hybrids of Cocoa Trees in Marginal Crop Areas in Côte d'Ivoire. *Agricultural Sciences*, **12**, 1508-1526.
https://doi.org/10.4236/as.2021.1212096

Received: August 30, 2021
Accepted: December 20, 2021
Published: December 23, 2021

Abstract

A study was carried out on 31 new hybrids in rain-deficient areas of Côte d'Ivoire. These areas were the regions of Djekanou, Toumodi and Yamoussoukro. The Divo region (favourable zone) was used as a control. The aim of this study was to determine the behaviour of these hybrids under drought conditions. The experimental setup was a Fischer block for each region. The treatments were the 31 families, with 3 replications and when the four regions were taken together, the study was a two-factor (region and family) trial. Drought caused increased mortality and specific leaf mass and reduced growth and development of progeny in rain-deficient areas. Five (5) progenies were found to be jointly successful in Divo, Djekanou and Yamoussoukro (F30, F15, F19, F31, and F33). On the other hand, 3 other families (F16, F36 and F29) also performing well in Divo were found in Toumodi.

Keywords

Drought, Resistant Hybrids, *Theombro cacao*, Côte d'Ivoire

1. Introduction

In recent years, with the onset of drought due to climate change, cocoa cultivation has been severely hampered in some areas in Côte d'Ivoire. The drought caused the deterioration of cocoa growing conditions with high mortality and a drop in production [1].

In this context of drought, the efforts of producers were in vain due to the lack of suitable plant material [2] [3]. When the minimum conditions for cocoa cultivation are met again in these marginal areas, then the return of this cultivation will be a great opportunity to reduce the pressure on the forest. Indeed, Ivorian forest cover has deteriorated considerably over the past 25 years with a conservation rate dropping from 16 million to 3.5 million hectares or 21.88% [4].

The cocoa program of the National Agronomic Research Center (CNRA) of Côte d'Ivoire, has produced high-performance varieties [5]. While these varieties tolerate certain biotic hazards such as diseases [6], their behavior in the face of drought linked to climate change is not understood. The purpose of this study is to assess the drought behavior of 31 new hybrids. Specifically, this involves determining mortality and evaluating the development and growth of hybrids.

2. Material and Methods

2.1. Plant Material

The plant material consists of 31 progenies obtained by controlled fertilization (**Table 1**). Thirty-six (36) plants were evaluated per progeny. A total of 4092 genotypes spread over 4 plots in four experimental sites with different rainfall patterns were monitored. These plants were installed on trial in 2018. They were 2 years old after planting at the time of the assessments.

Table 1. Descendants resulting from crosses between the parents.

Manual crossing			Progenies codes
Females		Males	
UPA402	X	UF676	F1
UPA409	X	IFC1	F2
UPA608	X	IFC412	F3
UPA603	X	UF667	F5
T85/799	X	IFC15	F7
SCA6	X	ICS1	F8
PA150	X	IFC5	F9
T79/501	X	IFC5	F10
IFC720	X	ICS46	F11
IMC67	X	IFC1	F12
MOQ413	X	SCA6	F13
POR	X	T60/887	F14
PA150	X	POR	F15
IFC303	X	IFC1	F16
SCA6	X	LAF1	F17
T60/887	X	IMC67	F19
PA150	X	T60/887	F20
P7	X	GU175A	F21

Continued

P7	X	GU284 A	F22
IFC303	X	GU284 A	F24
P7	X	IMC67	F25
P7	X	SCA6	F26
T60/887	X	IFC5	F27
NA32	X	IFC1	F28
PA150	X	T79/501	F29
T60/887	X	POR	F30
UPA413	X	SCA6	F31
P7	X	T60/887	F32
P7	X	PA150	F33
IMC67	X	T60/887	F35
POR	X	PA150	F36

2.2. Methods

2.2.1. Study Sites

The study was undertaken in four sites: Divo, Djekanou, Toumodi, and Yamoussoukro (**Figure 1**). The first site belongs to the favorable zone of cocoa culture in Côte d'Ivoire while the three later were found in unfavorable (marginal zone). Choice of plots for the study in the marginal zone was made by following the classification scale of favorable zones to cocoa cultivation. Four areas were chosen. These are Djekanou, Toumodi, Yamoussoukro (unfavorable area) and Divo (favorable area to cocoa cultivation and normal rainfall) which serves as a witness in our experiment. **Table 2** presents the climatic characteristics (rainfall and temperature) of these sectors.

2.2.2. Experimentation

The experimental design was a Fischer block for each region. The treatments were the 31 families, with 3 replicates of 12 trees each, for a total of 36 trees per family, for Divo, Djekanou and Toumodi and 3 replicates of 8 trees for Yamoussoukro. The standard density of 1333 trees per hectare (3 m between the rows and 2.5 m between the plants) was respected. When the four regions were taken together, the study was a two-factor (region and family) trial. A total of 4092 genotypes were evaluated.

2.2.3. Crop Management

The transfer of the seedlings to the different study sites was carried out after six months of residence of the seedlings in the nursery. Planting concerned vigorous plants. Plot maintenance consisted of manual weeding and the use of insecticide products (Califan super solicao and pyrical) as soon as symptoms of parasitism appeared, and of foliar fertiliser (califere) at a rate of 100 ml of insecticide in a 10-litre water sprayer.

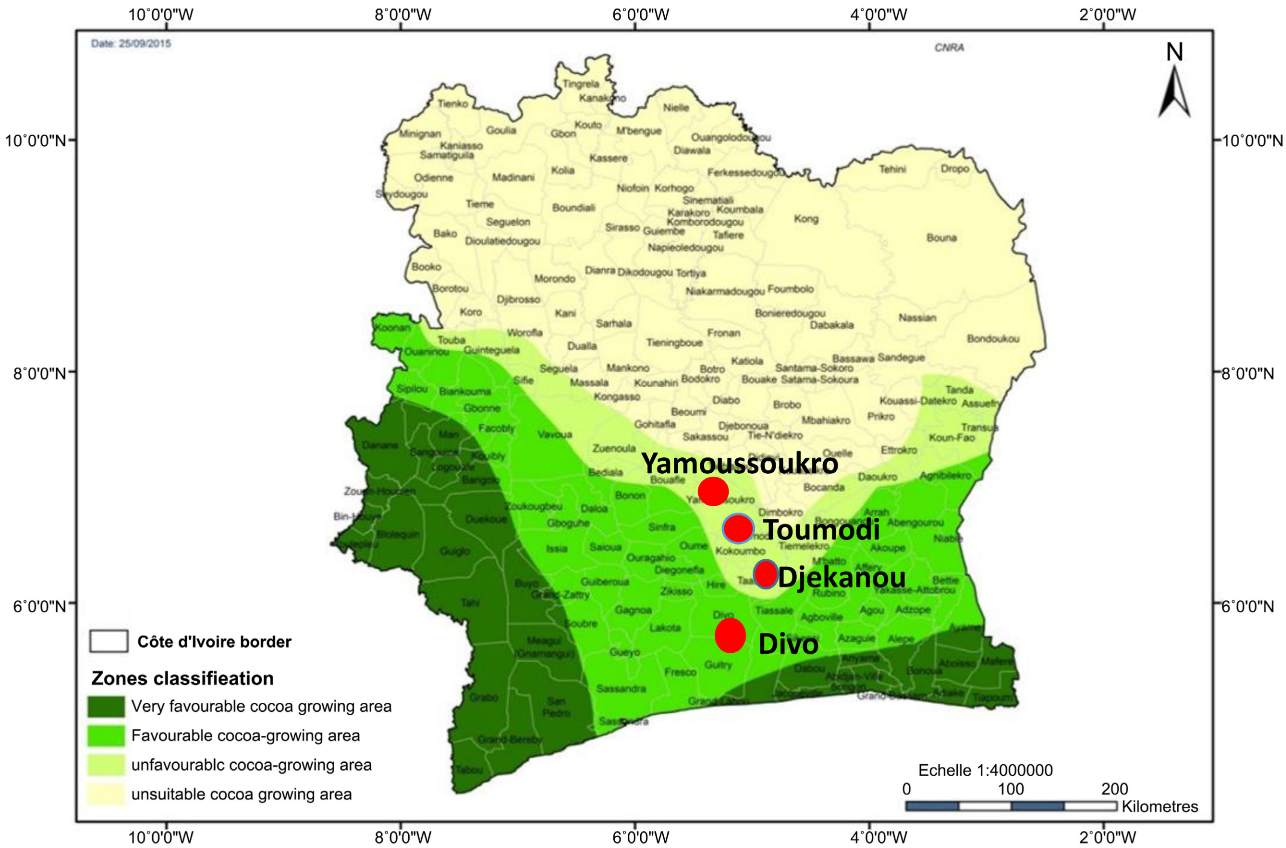

Figure 1. Study area.

Table 2. Rainfall and temperature of regions hosting the study sites.

	Rainfall (mm)			Temperatures (˚C)		
	Mini	**Maxi**	**Mean**	**Mini**	**Maxi**	**Mean**
Divo	24	249	1469	24.5	27.6	26.2
Djekanou	12	182	1092	25.2	28.3	26.6
Toumodi	12	180	1091	25.5	28.4	26.5
Yamoussoukro	12	170	1118	25.5	28.8	26.9

2.2.4. Parameters Assessed

Three types of parameters were evaluated: mortality rate, growth and development, and physiological parameters.

- ✓ **Mortality Rate**

The mortality rate was calculated 24 months after field planting. It is expressed as a percentage and corresponds to the ratio between the number of dead plants and the number of plants planted.

- ✓ **Growth and Development**

This is the collar diameter, the height of the plants, the crown rate and the leaf dimensions.

The collar diameter was measured at 10 cm from the ground with a caliper.

Plant height was measured from the ground to the apex of the trunk with a tape measure. The crown rate, expressed as a percentage, is the ratio of the number of crowned plants to the number of plants planted. The crown is the part of the cocoa tree that consists of a structured set of master branches or secondary shoots located at the top of the trunk. The height of the crown was measured with a tape measure; it is the length between the crown and the collar. The number of functional leaves per plant was counted. These are the green leaves, capable of photosynthesis. The dimensions, length and width of the leaves (three leaves per plant) were measured with a ruler and the leaf area was calculated according to the formula of [7]:

$$S\left(\text{cm}^2\right) = \frac{\pi ab}{4} \tag{1}$$

where $a = A/2$ and $b = B/2$; A = length, B = width. The total leaf area of the leaves was calculated by adding the elemental areas.

✓ **Physiological parameters** (water content and leaf density)

The water content of the leaves was calculated by the following formula:

$$TE\left(\text{mg/gMs}\right) = \frac{\left(MF - Ms\right)}{Ms} \tag{2}$$

with TE = water content; Mf = fresh mass and Ms = dry mass.

The specific leaf mass (SLM) was determined by the formula of [8]:

$$SLM\left(\text{mg/cm}^2\right) = \frac{MF}{SF} \tag{3}$$

with MF = fresh mass and SF = leaf area.

2.2.5. Statistical Analysis of the Data

The comparison of the hybrid families was done by analysis of variance, with a threshold p = 0.05. Pearson correlation was used to estimate the relationships between the agro-morphological and physiological variables. Principal component analysis (PCA) and hierarchical ascending classification (HAC) were used to reveal the strongest correlations between the variables and to assess the most discriminating ones for efficient selection of cocoa varieties at a young age, both overall and within the regions. These analyses were performed with SAS 9.4 (SAS Institute, 2018) and XLSTAT version 2014.

3. Results

3.1. Influence of Areas on the Behaviour of Young Cocoa Trees

The regions on all the families showed significant differences between them for all the parameters evaluated. The region * family interactions were significant for the parameters diameter at the collar, plant height, number of living leaves with a probability < 0.0001 and mortality rate with a probability of 0.01047. On the other hand, region * family interactions were not significant for the parameters crown rate (0.4847), crown height (0.8265), leaf area (0.9683), water content

(0.9961) and leaf specific gravity (0.8993) (**Table 3**). The mortality rate of young cocoa plants, twenty-four months after their establishment in the field, varied significantly according to the agro-climatic zones. It averaged 12.7% in Divo, which recorded the lowest average for all 31 families, compared to 68.01% for the Yamoussoukro zone, which showed the highest rate. Djekanou and Toumodi had intermediate averages of 21.9% and 49.7% respectively. The largest collar diameters were obtained by Divo with 1.64 cm and Toumodi with 1.6 cm. On the other hand, the smallest collar diameters were presented by the regions of Djekanou with 1.36 cm and Yamoussoukro with 1.28 cm. For plant height, Divo region had the highest value with 103.05 cm, and Yamoussoukro region the lowest with 70.26 cm. The number of living leaves was highest in Divo with 28.14 leaves, Djekanou with 23.86 leaves and Yamoussoukro with 22.77 leaves. On the other hand, the Toumodi region, with 9.58 live leaves, had the lowest number. For the crown rate, the regions of Djekanou with 14.39%, Divo with 12.44% and Toumodi with 10.48% were the best. The Yamoussoukro region with 3.80% had the lowest crowning rate. In terms of crown height, Divo with 70.87 cm and Djekanou with 67.05 cm were the best. The Yamoussoukro region with 13.36 cm had the lowest crown height. For leaf area, Divo region had the largest with 108.96 cm^2 and Yamoussoukro (51.32 cm^2) and Toumodi (43.15 cm^2) regions had the smallest areas. The highest water content was presented by the Divo region with 3951.5 mg/g and the lowest by the Yamoussoukro (1129.8 mg/g) and Toumodi (746.6 mg/g) regions. The highest specific leaf mass was obtained by the Yamoussoukro region with 7713 mg/cm^2 and the lowest by the Divo region with 656.6 mg/cm^2 (**Table 3**). The regions of Djekanou and Toumodi presented intermediate averages of 1600 mg/cm^2 and 1380.2 mg/cm^2 respectively.

Table 3. Comparison of experimental areas according to growth and development parameters of cocoa plants.

	Growth and development parameters							Physiological parameters	
Area	Rates of mortality %	Collar Diameter (cm)	height of plants (cm)	Rates of crown (%)	height of crown (cm)	number of living leaves	Total leaf area (cm^2)	Water Content (mg/g)	Specific leaf mass (mg/cm^2)
Divo	12.7 ± 10^a	1.64 ± 0.25^a	103.05 ± 10.66^a	12.44 ± 6.4^a	70.87 ± 33^a	28.14 ± 10.47^a	108.96 ± 35.53^a	3951.5 ± 1195.95^a	656.6 ± 11.54^c
Djekanou	21.9 ± 9^b	1.36 ± 0.16^b	87.89 ± 11.94^c	14.39 ± 8.92^a	67.05 ± 32.35^a	23.86 ± 8.43^b	67.52 ± 19.02^b	2306.7 ± 490.05^b	1600.8 ± 24.34^b
Toumodi	49.7 ± 17^c	1.60 ± 0.25^a	95.19 ± 13.08^b	10.48 ± 7.65^a	47.73 ± 23.32^b	9.58 ± 4.54^d	43.15 ± 27.72^c	746.6 ± 348.17^c	1380.2 ± 23.37^b
Yamoussoukro	68.01 ± 14.6^d	1.28 ± 0.29^c	70.26 ± 21.35^c	3.80 ± 6.03^b	13.36 ± 20.42^c	22.77 ± 17.58^c	51.32 ± 34.95^{cb}	1129.8 ± 674.77^c	7713 ± 75.47^a
Mean	38	1.51	93.66	11.06	48.74	22.36	76.57	2497.59	1710.8
CV (%)	49.52	36.56	34.14	13.93	81.56	43.15	133.91	154.24	103.25
$p \leq 0.05$	<0.0001	<0.0001	<0.0001	0.0045	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Region * family	0.01047	<0.0001	<0.0001	0.4847	0.8265	<0.0001	0.9683	0.9961	0.8993

In each column, the means followed by the same letter are not statistically different at the 5% level.

3.2. Growth and Development of Cocoa Trees in All Regions with Non-Significant Region * Family Interactions

The parameters with non-significant region * family interactions were crown rate, crown height, leaf area, water content and leaf specific mass. For these parameters, the families across all regions showed significant differences between them. Thus, the rankings of the families across all regions are the same for each region. For the crown rate, families F25 with 29.84%, F29 with 19.32% and F19 with 17.32% had the best crown rates. On the other hand, the lowest rates were obtained by families F17 (5.93%), F1 (5.76%) and F2 (5.14%). For crown height, families F35 with 76.59 cm and F22 with 70.03 cm had the best crown heights. On the other hand, the lowest height was obtained by family F24 with 11.45 cm. In terms of leaf area, families F19 with 115.12 cm^2 and F36 with 108.04 cm^2 had the largest areas. On the other hand, the smallest area was obtained by family F10 with 38.94 cm^2. Families F1 with 3468.1 mg/g and F19 with 3428.5 mg/g had the highest water content and families F10 (1486.7 mg/g) and F28 (1582.4 mg/g) the lowest. Families F36 (8088 mg/cm^2), F19 (8758 mg/cm^2), F32 (8527 mg/cm^2), F16 (8329 mg/cm^2), F15 (8134 mg/cm^2) had the highest specific leaf masses. On the other hand, families F13 (8.74 mg/$cm^{2)}$, F1 (10.84 mg/cm^2) and F12 (12.37 mg/cm^2) had the lowest masses (Table 4).

Table 4. Comparison of families across regions according to parameters with non-significant region * family interaction.

Family	Crown rate (%)	Crown height (cm)	Total leaf area (cm^2)	Water Content (mg/g)	Specific leaf mass (mg/cm^2)
F1	5.76 c	26.9 bc	89.92 ba	3468.1 a	10.84 c
F10	11.88 bc	35.35 bac	38.94 c	1486.7 c	19.75 bac
F11	10.2 bc	53.65 ba	68.34 bac	2820.4 ba	16.63 bac
F12	9.78 bc	53.82 ba	59.15 bac	1894.6 bc	12.37 c
F13	12.69 bac	66.8 ba	76.45 ba	2837.8 ba	8.74 c
F14	12.14 bac	31.32 bac	90.14 ba	2730.3 bac	20.46 bac
F15	12.82 bac	67.01 ba	87.01 ba	2908.7 ba	8134 a
F16	12.86 bac	64.34 ba	97.49 ba	2777.3 bac	8329 a
F17	5.93 c	35.21 bac	75.6 ba	2952.5 ba	7951 ba
F19	17.32 ba	62.73 ba	115.12 a	3428.5 a	8758 a
F2	5.14 c	26.92 bc	67.12 bac	2633.1 bac	6934 bac
F20	11.62 bc	65.58 ba	80.59 ba	2541.3 bac	7585 ba
F21	7.8 bc	48.17 bac	74.88 ba	2188 bac	6185 bac
F22	8.48 bc	70.03 a	69.14 bac	2597.1 bac	6690 bac
F24	14.6 bac	11.45 c	74.03 ba	2267.5 bac	6400 bac
F25	29.84 a	65.03 ba	70.06 ba	1971.6 bc	5405 bc
F26	12 bac	57.21 ba	79.76 bac	1911.6 bc	6159 bac

Continued

F27	10.4 bc	33.08 bac	60.04 bac	1934.7 bc	5818 bc
F28	6.64 bc	61.99 ba	39.75 bc	1582.4 c	4238 c
F29	19.32 ba	45.54 bac	71.06 ba	2341.9 bac	6575 bac
F3	14.72 bac	43.14 bac	77.63 ba	2245.2 bac	6598 bac
F30	10.47 bc	66.95 ba	97.51 ba	2726.4 bac	7880 ba
F31	12.41 bac	45.38 bac	76.63 ba	2688.2 bac	7236 ba
F32	7.76 bc	35.29 bac	88.29 ba	3097.8 ba	8527 a
F33	11.1 bc	49.74 bac	89.98 ba	2893.5 ba	7436 ba
F35	14.74 bac	76.59 a	76.68 ba	2531.3 bac	7038 ba
F36	12.95 bac	39.64 bac	108.04 a	2780 bac	8088 a
F5	8.64 bc	24 bc	63.85 bac	2085.4 bac	6723 bac
F7	11.05 bc	34.31 bac	50.59 bac	2014 bac	5581 bc
F8	15.07 ba	67.03 ba	80.42 ba	2608.8 bac	7558 ba
F9	12.95 bac	54.86 ba	73.67 ba	2595.7 bac	7383 ba
Mean	11.06	48.74	76.57	2490	7004.4
CV (%)	13.93	81.56	133.91	78.15	9.87
$p \leq 0.05$	0.0045	<0.0001	<0.0001	<0.0001	<0.0001
region * family	**0.4847**	**0.8265**	**0.9683**	**0.9961**	**0.8993**

3.3. Growth and Development of Cocoa Trees Region by Region with Significant Region * Family Interactions

The parameters with significant region * family interactions were mortality rate, collar diameter, plant height and number of living leaves. For these parameters, family rankings were made by region. Mortality rate showed a significant difference between families in Divo and Toumodi and homogeneity in Djekanou and Yamoussoukro (Table 5). The highest mortality rates were obtained by family F19 (39%) in Divo and families F2 (80.67%), F7 (75%), F19 (83%) and F31 (78%) in Toumodi. On the other hand, the lowest mortality rates were presented by families F1 (4.05%), F5 (4.05%), F9 (4.05%), F10 (4.05%), F21 (2.08%), F22 (5.04%), F32 (3.56%) and F35 (2.08%) at Divo and family F29 (19.33%) at Toumodi.

Collar diameter showed a significant difference between families in all regions. The best collar diameters were obtained by family F19 (2.43 cm) in Divo, F31 (1.77 cm) in Djekanou, F14 (2.01 cm) and F16 (2.02) in Toumodi and F31 (2.15 cm) in Yamoussoukro. On the other hand, the smallest diameters at the collar were presented by families F7 (1.22 cm) and F17 (1.33 cm) in Divo, F1 (1.14 cm) and F28 (1.04 cm) in Djekanou, F1 (1.14 cm) and F13 (1.08 cm) in Toumodi and F1, F2, F3, F5, F7, F8, F9, F10, F11, F13, F14, F16, F17, F20, F21, F22, F25, F27, F32, F35 and F36 with values that varied from 1 to 1.28 cm in Yamoussoukro (Table 5).

Table 5. Comparison of families according to mortality rate and crown diameter (parameters with significant region * family interaction) within regions.

	Mortality rate (%)				Collar diameter (cm)			
Family	Divo	Djekanou	Toumodi	Yamoussoukro	Divo	Djekanou	Toumodi	Yamoussoukro
F1	4.05 dc	22.33 a	61 ba	73.22 a	1.74c bd	1.14 ef	1.14 ed	1.05 b
F10	4.05 dc	33.67 a	36 bac	50.14 a	1.40 cbd	1.31 edfc	1.47 ebdac	1.08 b
F11	8 bdc	30.67 a	69.33 ba	68.48 a	1.35 cbd	1.23 edfc	1.36 ebdc	1.04 b
F12	11 bdc	33.33 a	36 bac	72.62 a	1.42 cbd	1.23 edfc	1.77 bdac	1.35 ba
F13	7.05 bdc	9.03 a	52.67 bac	99.58 a	1.68 cbd	1.16 edf	1.08 e	1 b
F14	11.69 bdc	25.0 a	36.33 bac	60.14 a	1.63 cbd	1.35 edfc	2.01 a	1.26 b
F15	24.66 bdac	11.0 a	44.67 bac	37.67 a	1.88 cbd	1.47 ebdac	1.55 ebdac	1.34 ba
F16	33.33 ba	25.0 a	36 bac	77.48 a	2.04 b	1.40 ebdfc	2.02 a	1.22 b
F17	11.69 bdc	36.33 a	36.33 bac	85.81 a	1.33 cd	1.34 edfc	1.65 ebdac	1 b
F19	39 a	17.0 a	83 a	78.77 a	2.43 a	1.57 bac	1.6 ebdac	1.85 ba
F2	30.67 bac	41.67 a	80.67 a	72.62 a	1.49 cbd	1.27 edfc	1.5 ebdac	1.02 b
F20	11 bdc	17.36 a	41.33 bac	72.62 a	1.64 cbd	1.35 edfc	1.60 ebdac	1.07 b
F21	2.08 d	19.33 a	47.33 bac	65.14 a	1.62 cbd	1.41 ebdfc	1.74 bdac	1.11 b
F22	5.04 dc	13.54 a	42 bac	54.72 a	1.39 cbd	1.39 ebdfc	1.44 ebdac	1 b
F24	16.67 bdac	11.0 a	66.33 bac	50.67 a	1.53 cbd	1.21 edfc	1.78 bac	1.45 ba
F25	23 bdac	16.67a	58 bac	72.62 a	1.65 cbd	1.20 edfc	1.38 ebdac	1.02 b
F26	14.69 bdc	25a	55.67 bac	61.81 a	1.75 cbd	1.53 ebdac	1.75 bdac	1.86 ba
F27	11 bdc	27.67 a	36 bac	66.81 a	1.61 cbd	1.27 edfc	1.81 bac	1.18 b
F28	7.05 bdc	9.03 a	61.33 bac	83.44 a	1.36 cbd	1.04 f	1.59 ebdac	1.6 ba
F29	14.69 bdc	14.69 a	19.33 c	34.37 a	1.55 cbd	1.29 edfc	1.75 bdac	1.51 ba
F3	6.03 bdc	25.33 a	36 bac	65.14 a	1.89 cbd	1.33 edfc	1.63 ebdac	1.09 b
F30	6.03 bdc	13.67 a	38.67 bac	74.1 a	1.77 cbd	1.478 ebdac	1.22 ebdc	1.62 ba
F31	11 bdc	22.33 a	78 a	80.48 a	1.9 cbd	1.77 a	1.175 edc	2.15 a
F32	3.56 dc	13.02 a	50 bac	41.11 a	1.74 cbd	1.31 edfc	1.51 ebdac	1.19 b
F33	9.72 bdc	14.0 a	69.33 ba	83.44 a	1.86 cbd	1.47 ebdac	1.3 ebdc	1.37 ba
F35	2.08 d	36.0 a	52.67 bac	76.14 a	1.44 cbd	1.56 bdac	1.55 ebdac	1.26 b
F36	7.05 bdc	16.67 a	47.33 bac	63.81 a	1.96 cb	1.74 ba	1.51 ebdac	1.28 b
F5	4.05 dc	20.36 a	25.33 bc	85.29 a	1.47 cbd	1.24 edfc	1.8 ba	1.2 b
F7	33.33 ba	41.67 a	75 a	72.97 a	1.22 d	1.54 ebdac	1.178 edc	1.2 b
F8	16.33 bdac	25.0 a	22.33 bc	61.85 a	1.68 cbd	1.367 edfc	1.86 ba	1.2 b
F9	4.05 dc	11.0 a	47.33 bac	65.33 a	1.54 cbd	1.34 edfc	1.61 ebdac	1.03 b
moyenne	12.79	21.87	49.89	67.77	1.64	1.36	1.61	1.28
CV (%)	10.99	14.71	29.67	24.18	44.71	30.23	29.66	32.56
$p \leq 0.05$	<0.0001	0.1522	<0.0001	0.9834	<0.0001	<0.0001	<0.0001	<0.0001

In each column, the means followed by the same letter are not statistically different at the 5% level.

Plant height showed a significant difference between families in all regions (Table 6). The greatest plant heights were obtained by families F13 (118.62 cm), F15 (124.79 cm), F19 (122.92 cm) and F31 (116.53 cm) in Divo, F31 (113 cm) and F36 (109.3 cm) in Djekanou, F8 (107.29 cm), F14 (112.78 cm), F16 (114.57 cm), F26 (114.44 cm), F28 (107.79 cm) and F29 (111.07 cm) in Toumodi and F19 (118 cm) and F31 (120.5 cm) in Yamoussoukro. On the other hand, the smallest plant heights were shown by families F7 (81.48 cm), F10 (87.16 cm), F17 (86.94 cm) and F35 (87.17 cm) in Divo, F2 (71.38 cm) F5 (72.35 cm), F11 (73.96 cm), F24 (70.69 cm) and F25 (71.07 cm) in Djekanou, F31 (64.38 cm) in Toumodi and F2 (36.5 cm), F13 (36.6 cm) and F22 (39.71 cm) in Yamoussoukro.

The number of live leaves showed a significant difference between families in all regions. The highest numbers of live leaves were obtained by families F19 (62.46 leaves) and F31 (49.81 leaves) in Divo, F19 (38.93 leaves), F31 (50.75 leaves) and F36 (36.76 leaves) in Djekanou, F14 (21.44 leaves) in Toumodi and F19 (67 leaves), F26 (49.63 leaves) and F31 (77 leaves) in Yamoussoukro. On the other hand, the smallest number of living leaves was presented by families F7 (12.67 leaves) in Divo, F1 (13.43 leaves) in Djekanou, F25 (1.8 leaves) and F28 (0.57 leaves) in Toumodi and F1, F2, F3, F5, F7, F9, F10, F11, F12, F13, F14, F15, F16, F17, F20, F21, F22, F25, F27, F28, F32, F35 and F36 with values that varied from 6.33 to 27 live leaves in Yamoussoukro (Table 6).

Table 6. Comparison of families according to height and number of living leaves parameters with significant region * family interaction) within regions.

	Plant heights (cm)				Number of living leaves			
Family	Divo	Djekanou	Toumodi	Yamoussoukro	Divo	Djekanou	Toumodi	Yamoussoukro
F1	100.05 bdac	82.46 bac	83.29 ba	61.25 ba	34.17 bcd	13.43 e	3.79 bc	10.5 c
F10	87.16 dc	78.85 bac	89.61 ba	59.82 ba	26.11 bcd	16.21 ed	10.13 bac	17.18 c
F11	97.14 bdac	73.96 c	87.55 ba	65.6 ba	19.70 cd	18.48 ced	12.636 bac	13.43 c
F12	94.57 bdc	82 bac	94.13 ba	68.08 ba	20.41 cd	21.13 cebd	7.30 bc	16.83 c
F13	118.62 ba	88.65 bac	75 ba	36.6 b	38.09 bcd	15.77 ed	3.71 bc	7.51 c
F14	95.40 bdc	80.48 bac	112.78 a	60.5 ba	26.81 bcd	18.11 ced	21.44 a	20.22 c
F15	124.79 a	101.03 bac	85.55 ba	73.46 ba	40.22 bc	29.81 cebd	8.7 bac	25.33 c
F16	110.98 bac	86.67 bac	114.57 a	74.6 ba	40.36 bc	33.19 cbd	13.48 bac	23 c
F17	86.94 dc	74.65 bc	101.52 ba	51.53 ba	21.47 cd	27.57 cebd	8.57 bac	11.33 c
F19	122.92 ba	97.2 bac	81.17 ba	118 a	62.46 a	38.93 b	6.67 bc	67 ba
F2	94.68 bdc	71.38 c	92.43 ba	36.5 b	17.88 cd	17.10 ed	9.57 bac	8.83 c
F20	104.59 bdac	89.87 bac	90.76 ba	50.83 ba	23.91 cd	20.33 ced	17.38 ba	6.33 c
F21	99.92 bdac	85.41 bac	97.11 ba	61.94 ba	23.61 cd	24.45 cebd	7.05 bc	12.38 c
F22	93.74 bdc	102.91 bac	101.43 ba	39.71 b	18.65 cd	29.67 cebd	4.29 bc	8 c
F24	101.09 bdac	70.69 c	104.92 ba	82.59 ba	25.5 bcd	16.56 ed	10.42 bac	38.82 bc
F25	99.49 bdac	71.07 c	74.2 ba	57.75 ba	23.96 cd	16.33 ed	1.8 c	7.5 c

Continued

F26	105.88 bdac	103.96 bac	114.44 a	102.38 ba	25.26 bcd	30.44 cebd	5.94 bc	49.63 bac
F27	110.75 bac	80.39 bac	101.91 ba	57.76 ba	28.97 bcd	21.73 cebd	11.91 bac	21.43 c
F28	96.22 bdac	74.97 bc	107.79 a	101 ba	17.29 cd	14.42 ed	0.57 c	27 c
F29	108.30 bdac	92.97 bac	111.07 a	83.65 ba	23.23 cd	17.84 ced	5.83 bc	32.33 bc
F3	106.36 bdac	88 bac	92.52 ba	63.56 ba	31.17 bcd	17.89 ced	9.09 bac	11.88 c
F30	105.45 bdac	104.61 bac	73.23 ba	93.28 ba	34.09 bcd	30.13 cebd	9.86 bac	52 bac
F31	116.53 ba	113 a	64.38 b	120.5 a	49.81 ba	50.75 a	5.13 bc	77 a
F32	106.69 bdac	83.76 bac	87.43 ba	70.11 ba	33.23 bcd	20.31 ced	10.87 bac	16.35 c
F33	103.80 bdac	98.61 bac	87.45 ba	87.83 ba	25.67 bcd	29.61 cebd	6.18 bc	31.33 bc
F35	87.17 dc	92.09 bac	88.12 ba	83.76 ba	26.26 bcd	28.91 cebd	6.94 bc	18 c
F36	115.77 bac	109.3ba	96.05 ba	78.56 ba	37.94 bcd	36.76 cb	8.68 bac	16.25 c
F5	100.22 bdac	72.35 c	102.52 ba	62.33 ba	19.91 cd	18.86 ced	12.48 bac	7.37 c
F7	81.48 d	96.90 bac	76.33 ba	56.38 ba	12.67 d	27.38 cebd	5.22 bc	21.5 c
F8	105.36 bdac	84.63 bac	107.29 a	57.4 ba	31.7 bcd	22.19 cebd	16.32 ba	29 bc
F9	113.85 bac	88.94 bac	92.68 ba	51.38 ba	16.94 cd	19.72 ced	11.37 bac	10.25 c
Mean	103.05	87.9	95.19	70.26	28.14	23.86	9.58	22.767
CV (%)	30.19	39.88	32.83	43.21	45.23	39.14	55.36	39.84
p ≤ 0.05	<0.0001	<0.0001	<0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001

In each column, the means followed by the same letter are not statistically different at the 5% level.

3.4. Correlation between Mortality Rate, Development and Growth Parameters and Physiological Parameters

The Pearson correlation matrix (Table 7) revealed the strongest relationships between mortality rate, development and growth parameters and physiological parameters of young cocoa trees. Thus, development and growth parameters such as crown diameter, plant height, crown height, number of live leaves and leaf area were negatively correlated with mortality rate respectively (−0.52), (−0.72), (−0.89), (−0.96), (−0.5) and (−0.81). Similarly, leaf specific mass, a physiological parameter was negatively correlated with development and growth parameters respectively (−0.78), (−0.94), (−0.92), (−0.94) and (−0.47) except for the number of living leaves. Also, water content, a physiological parameter was negatively correlated with mortality rate (−0.87) and positively correlated with total leaf area (0.94).

3.5. Projection of Regions According to Development and Physiological Variables of Cocoa Genotypes in Design 1 and 2

The share of information returned by the two selected axes of the principal component analysis of the regions was 94.27%. Axis 1 expressed 77.67% of the total variability. The variables well represented on this axis were crown diameter, height, crown ratio, crown height, total leaf area and leaf water content with

Table 7. Pearson correlation matrix between developmental physiological and mortality variables.

variables	diam	haut	Tx cour	hautcou	nfv	sft	te	msf	tau mort
Diam	1								
Haut	**0.77**	1							
Tx Cour	0.49	**0.53**	1						
Hautcou	**0.56**	**0.59**	**0.91**	1					
Nfv	**0.69**	**0.57**	0.36	0.46	1				
Sft	0.49	0.4	0.21	0.28	**0.53**	1			
Te	0.4	0.33	0.15	0.22	0.47	**0.94**	1		
msf	**−0.78**	**−0.94**	**−0.92**	**−0.94**	0.48	**−0.47**	**−0.50**	1	
tau mort	**−0.52**	**−0.72**	**−0.89**	**−0.96**	**−0.50**	**−0.81**	**−0.87**	**0.82**	1

Values in bold are different from 0 with a significance level of $p < 0.000$. Diam=collar diameter; high = plant height; tx yard = crown rate. high yard = crown height. nfv = number of living leaves. sft = total leaf area. te = water content. msf = leaf specific gravity.

squared cosines ranging from 0.6758 to 0.9230. This axis was the axis of developmental, growth parameters. Axis 2 expressed 16.58% of the total variability. The variable that was well represented on this axis was the number of living leaves with a cosine square of 0.6668. This axis was the axis of a physiological parameter (leaf specific mass) and the mortality rate. The projection of the 4 regions according to the agro-morphological and physiological variables of the cocoa genotypes along axes 1 and 2 is presented in Figure 2. The hierarchical ascending classification of regions gave three classes. Thus the Divo region, which constituted the first class, was home to the progenies with the best development and growth (large diameters, large sizes with more crowns, large crown heights with more functional leaves, with the largest leaf areas, the highest water content), small specific leaf masses and the lowest mortality rate. The regions of Djekanou and Toumodi, which constituted the second class, were home to progenies with intermediate traits. The Yamoussoukro region, which constituted the third class, was home to progenies with poor development and growth except for mortality rate and specific leaf mass.

3.6. Projection of Progenies as a Function of Developmental and Physiological Variables of Cocoa Genotypes in Planes 1 and 2

The information returned by the two axes retained from the principal component analysis of the families expressed 64.84% of the observed variability. Axis 1 expressed 46.95% of the total variability. The variables collar diameter, plant height, number of living leaves, total leaf area, water content and specific leaf mass constructed this axis of physiological and vigour parameters with squared cosines that varied from 0.5739 to 0.8563. Axis 2 expressed 17.89% of the total variability. The variables crown rate with a squared cosine of 0.5123, crown height with a squared cosine of 0.3702 and mortality rate with a squared cosine

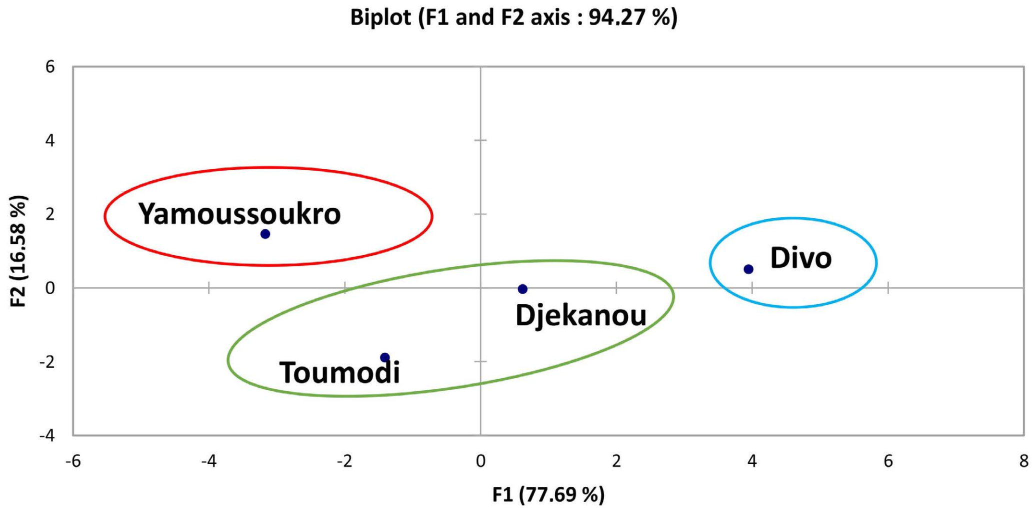

Figure 2. Projection of regions in the 1 - 2 plane according to agro-morphological and physiological parameters.

of 0.8070, constructed this axis of earliness and drought susceptibility (**Figure 3** and **Figure 4**). The results show that within each experimental site after the hierarchical ascending classification, the performance of the families varies significantly between them. Not all families performed equally well and did not rank equally across regions. Indeed, of the 15 best families that were characterised by large crown diameter, large height, large number of living leaves, large leaf area, high water content and low leaf density in Divo (**Figure 3(A)**), however, of these, only 5 (F30, F15, F19, F31, and F33) were also found to be among the best performers at Djekanou (**Figure 3(B)**) and Yamoussoukro (**Figure 4(A)**). None of them were found among the best performers in Toumodi. On the other hand, three other families (F16, F36 and F29) that also performed well in Divo were found in Toumodi (**Figure 4(A)**) and another (F24) was found to perform well in Yamoussoukro. In the end, the majority of families performing in Toumodi were not found performing in Divo, Djékanou and Yamoussoukro.

4. Discussion

The 31 progenies showed highly variable behaviour depending on the evaluation parameters considered.

Thus, the results obtained showed a depressive effect of drought on cocoa varieties. This depressive effect was observed in regions with deficient rainfall such as Toumodi and Yamoussoukro, unlike the control region in a normal rainfall zone (Divo). In this study, progenies showed a decrease in crown diameter and plant height in dry areas. Our results are in line with those of [9] [10] [11] and [7], who showed that vegetative growth (diameter and height) discriminated between water-stressed and drought-stressed varieties. In our study, progenies also showed a reduction in leaf density as well as leaf area in rainfall-deficient areas. [12] stated that one of the first reactions of plants to water deficit is to reduce

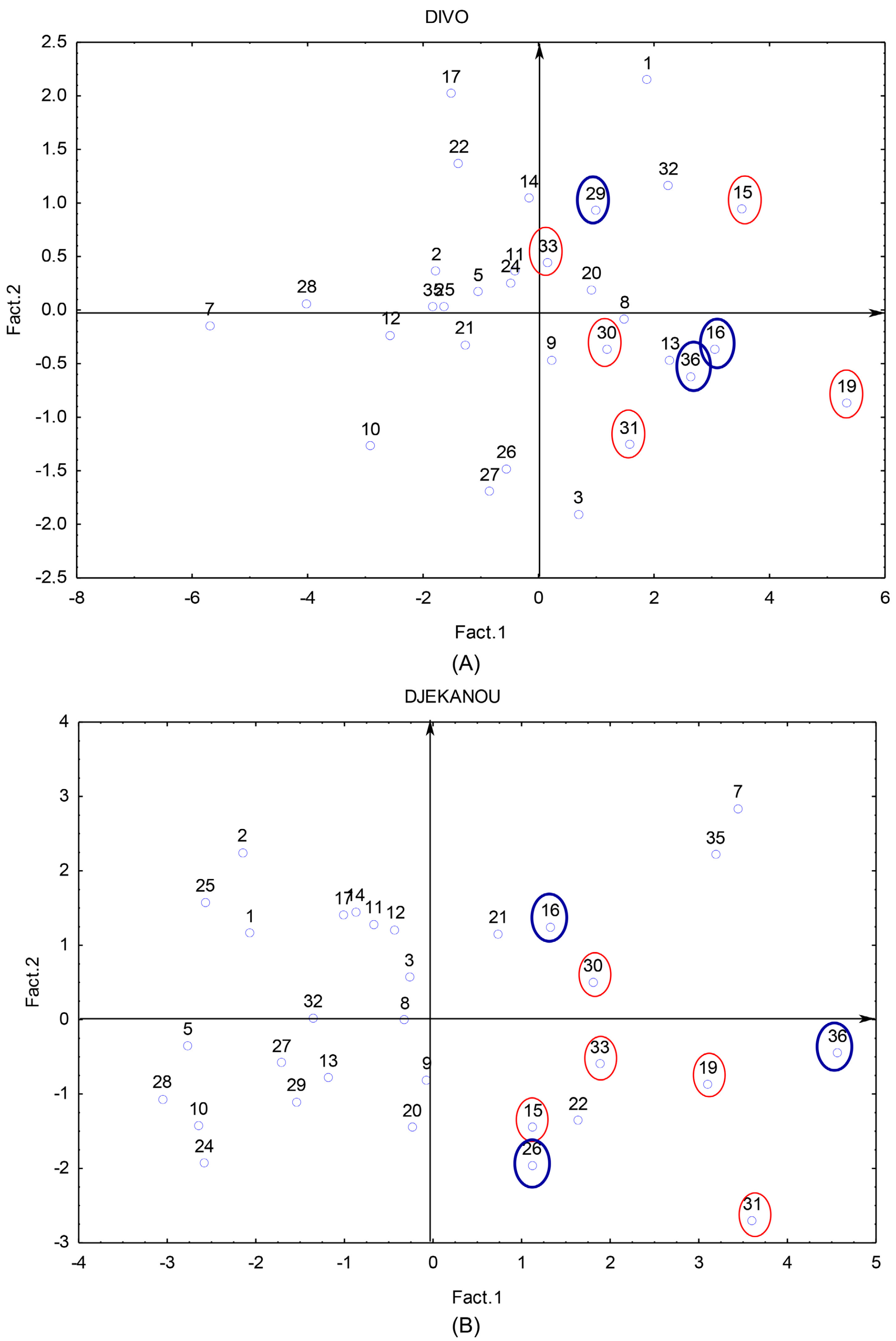

Figure 3. projection of the progenies of the Divo and Djekanou regions on the principal component analysis planes 1 - 2. (A) projection of Divo progenies in the 1 - 2 plane (The different numbers correspond to the codes of the progenies); (B) Projection of Djekanou progenies in the 1 - 2 plane (The different numbers correspond to the codes of the progenies).

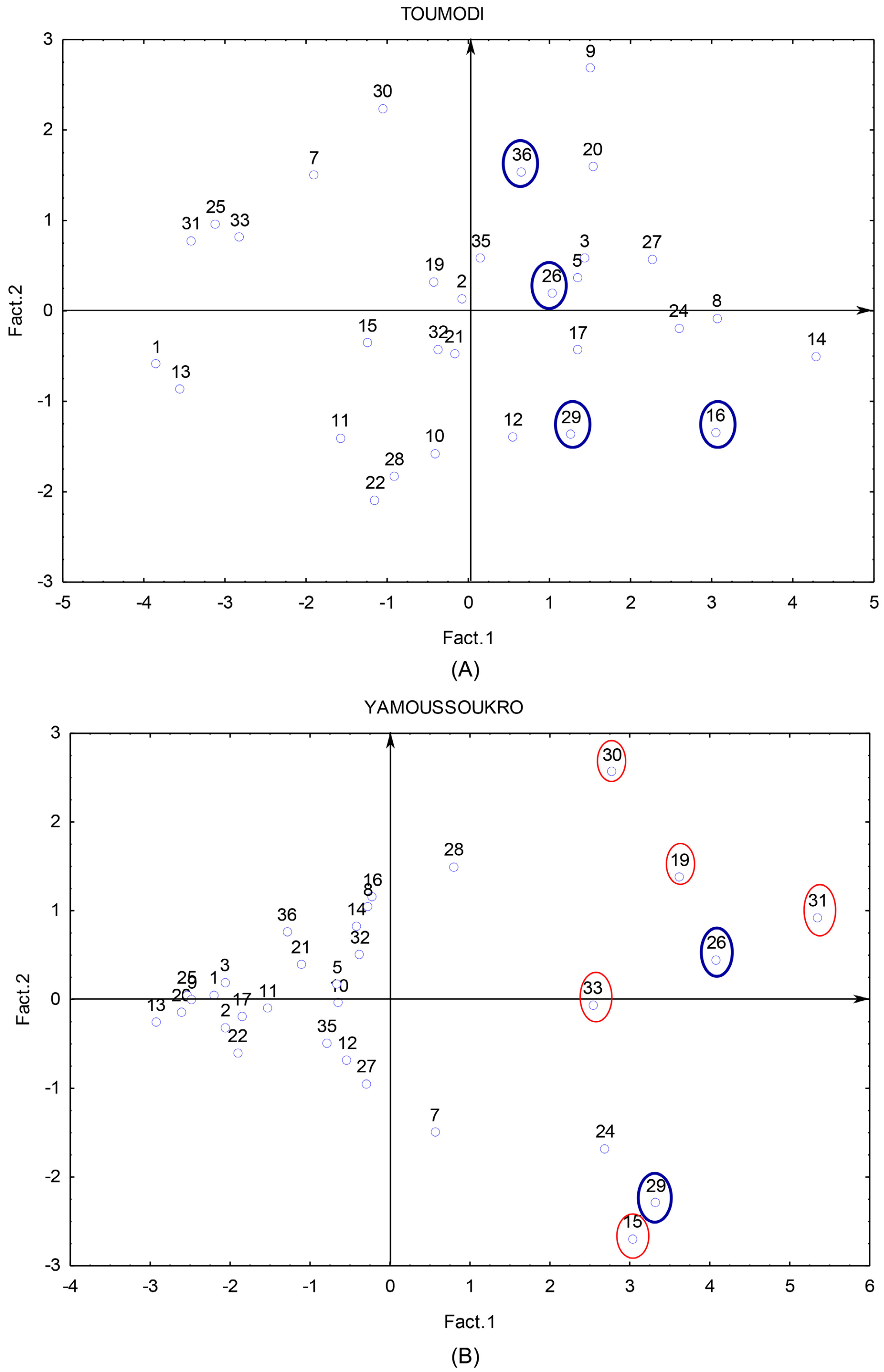

Figure 4. Projection of the progenies of the Toumodi and Yamoussoukro regions on the principal component analysis planes 1 - 2. (A) projection of Toumodi progenies in the 1 - 2 plane (The different numbers correspond to the codes of the progenies); (B) Projection of Yamoussoukro progenies in the 1 - 2 plane (The different numbers correspond to the codes of the progenies).

leaf area and the number of functional leaves. Our results also confirm those of [13], who demonstrated that vegetative development under conditions of limited water supply is strongly disturbed, mainly by a significant decrease in the number of functional leaves and leaf area. This decrease in vegetative development is one of the responses of plants to dehydration, in order to conserve water resources and allow the survival of the plant [12]. The effect of water stress due to drought can result, depending on the adaptive strategy of each progeny or variety, in morphological modifications. These modifications affect primary growth [7] [14] [15], thus reducing turgidity and consequently the expansive power of the leaves and favouring the proper development of the underground system [16]. According to [17], leaves of water-stressed plants usually reach smaller final sizes than those of the control.

Water stress due to drought is a determining factor for plant growth in semi-arid regions. It is expressed by a progressive slowing down of primary growth [7] [15], marked by the reduction of leaf cell turgidity. Our study revealed a reduction in leaf water content of progenies in rainfall-deficient areas in Toumodi and Yamoussoukro, in contrast to Divo, a normal rainfall area. Our results corroborate those of [18], who showed that water shortage due to drought induced a decrease in relative water content in stressed plants. [19], noted the same finding and suggested the use of water content as an indicator of the water status of the plant under stress. The water content of cocoa leaves seems to decrease proportionally with the reduction of water content in the soil [20]. [15] noted that this decrease in water content is more rapid in susceptible varieties than in resistant varieties. On the other hand, a high water content under stress conditions has been observed in soybean [21]. On the other hand, [22] showed that genotypes that maintain a high water content in the presence of water stress are tolerant genotypes. Thus, the best progenies from the Yamoussoukro region and the Toumodi region (drier areas) with the highest water content values would appear to be potentially drought tolerant.

The specific leaf mass is one of the important markers in the response of plants to water stress. It can be considered as a simple criterion for selecting genotypes with high water use efficiency under water deficit conditions [23]. The specific leaf mass of progenies in rainfall-deficient areas was higher than in normal rainfall areas. Our results are in line with those of [23] who showed the increase in leaf density in some plants under stress. According to the same author, the increase in specific leaf mass in plants under stress was highly correlated with the reduction in leaf area. Indeed, in this study, the negative correlation ($r = -0.47$) between specific leaf mass and leaf area confirms this assertion. Indeed, the process of reducing leaf area and increasing leaf specific mass allows plants to "confront" the lack of water by reducing transpiration [23].

5. Conclusion

The study of the response to drought in the 31 cocoa progenies tested revealed the existence of a large variability for most of the parameters measured. The effect of drought was well marked between regions with deficient rainfall such as Toumodi and Yamoussoukro and those with normal rainfall such as Divo and Djekanou, which seems to be a transition region. Thus, mortality rate and specific leaf mass increased, crown diameter, plant height, leaf area and leaf water content decreased in cocoa trees tested in rainfall-deficient areas. Highly significant positive and negative correlations between agro-morphological and physiological variables were found. The F1, F11, F14, F16, F19, F21, F26, F30, F31, F32, F33 and F36 progenies behaved well in all 4 regions. The significance of the region * family interaction (p = 0.001) showed that the progeny behaved differently from one area to another, depending on the degree of drought severity. Thus, among the fifteen (15) best progenies in Divo (F1, F13, F15, F16, F19, F20, F29, F30, F31, F32, F33, F36, F3, F8 and F9), only five (F30, F15, F19, F31, and F33) repeated the same performance in Djekanou and Yamoussoukro. In addition, 3 other families (F16, F36 and F29) that also performed well in Divo were found in Toumodi. These progenies seemed to adapt well to the drought and were better respectively in Divo (normal rainfall zone) and Djekanou, Yamoussoukro and Toumodi (deficit rainfall zone).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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