eISSN: 1984-3909
Coffee Science, e171994, 2022

Doi: https://doi.org/10.25186/.v17i.1994

Identifying *Coffea* genotypes tolerant to water deficit

Diana Molina[1], Ruben Medina Rivera[2]

[1]Centro Nacional de Investigaciones de Café/Cenicafé, Plant Breeding Department, Manizales, Caldas, Colombia
[2]Centro Nacional de Investigaciones de Café (Cenicafé), Biometrics Department. Manizales, Caldas, Colombia.
Corresponding author: diana.molina@cafedecolombia.com; ruben.medina@cafedecolombia.com
Received in December 8, 2021 and approved in May 9, 2022

ABSTRACT

Approximately 26% of the coffee grown in Colombia is located in areas presenting water deficit, with some of these areas also presenting high solar brightness. This combination reduces coffee production, thus affecting the income of 31% of the country's coffee-growing families. To identify accessions of the Colombian Coffee Collection (CCC) that are tolerant to water deficit, 65 genotypes were evaluated in screenhouse conditions at the National Coffee Research Center (Cenicafé), located in Manizales, Caldas, Colombia. Seedlings of each genotype were transplanted to polyethylene bags, each filled with 10 kg sandy loam Andisol soil. Two moisture treatments were applied as follows: (1) soil at field capacity (60% moisture) and (2) water deficit conditions, with soil at 50% field capacity (30% moisture). After five months, total dry biomass was determined, considered as the sum of the dry biomass of leaves, stems, and roots. The Student's t test for independent samples was used to analyze resulting values at a level of significance of 5%. Reducing irrigation under water deficit conditions usually delays accession growth, which is reflected in decreased biomass. However, the total dry biomass of nine Ethiopian introductions of *Coffea arabica* (CCC238, CCC254, CCC284, CCC372, CCC474, CCC536, CCC537, CCC555, CCC1147), six diploid accessions (CCC1030, EA.20, EA.209, EA.227, EA.229, EA.287), and three interspecific hybrids of Caturra x *Coffea canephora* (25, 640, 702) in water deficit conditions did not differ statistically from the total dry biomass obtained in treatments with irrigation at field capacity. Because these introductions present adaptation mechanisms to water deficit, they retain their leaves without reducing their leaf area or total dry biomass and should accordingly be considered as candidates for evaluation in dry regions to determine their tolerance to water deficit based on effects on production or biomass.

Key words: *Coffea arabica; Coffea canephora;* interspecific hybrids; total dry biomass; water stress.

1 INTRODUCTION

Coffee is one important commodity in the global market, being planted on 11 million ha in 82 developing countries, with a world production of around 10 million tons green coffee (FAOSTAT, 2022). Water deficit is an important abiotic stress that limits agricultural production (Guedes et al., 2018) and becomes increasingly relevant in the case of perennial crops such as coffee (Cheserek; Gichimu, 2012) that has a life cycle of up to 30 years, but can live more than 50 years (Bunn et al., 2015). DaMatta and Ramalho (2006) also found that water shortage and unfavorable temperatures considerably affect coffee yield. According to the Intergovernmental Panel on Climate Change (IPCC, 2021), the tropics and sub-tropics will be increasingly more vulnerable to climate change; which could lead to the establishment of coffee crops in suitable areas at higher elevations (Ovalle-Rivera et al., 2015). Crop losses due to pests such as *Hypothenemus hampei* Ferrari have also been estimated to increase by up to 24% (Fernandes et al., 2011), and pest infestation has spread to higher altitudes ranging from 1,200 to 1,800 m.a.s.l (Jaramillo et al., 2011). In addition, wild *Coffea* populations will be increasingly more sensitive to extinction, especially in these scenarios (Davis et al., 2019).

Although 130 species have been identified in the *Coffea* genus (Davis; Rakotonasolo, 2021), only *Coffea arabica* L. and *Coffea canephora* Pierre ex A.Froehner are being commercialized, the former accounting for 70% of global production and the latter for the remaining 30%. *Coffea arabica* is the only species grown in Colombia. Its economic importance lies in the fact that this crop ranks first in area planted countrywide, covering 837,341 ha and presenting a 2020 harvest value of COP$ 10,768,530 (Federación Nacional de Cafeteros de Colombia, 2022a). Coffee growing is the livelihood for 546.382 coffee-grower families, mostly on small and medium-sized farms that cover areas between 0.5–5 ha. In other words, about two million people depend directly on this crop (Federación Nacional de Cafeteros de Colombia, 2022b).

The severity of the damage caused by drought is generally unpredictable as it depends on several factors including rainfall distribution (Jaramillo, 2018), moisture holding capacity of the soil, and water losses due to evapotranspiration (Fahad et al., 2017). Drought affects plant growth, nutrient assimilation, photosynthesis, assimilate partitioning, and crop yield (Fahad et al., 2017). The magnitude of coffee harvest losses in Colombia depends on the damage caused by water deficiency during flowering and the berry-filling stage (Jaramillo; Arcila, 1996; Arcila; Jaramillo, 2003; Jaramillo, 2018). The El Niño event that occurred from 2015 to 2016 had a strong impact on coffee crops in the main coffee-producing departments of the country, due to the increase in floating berries, poorly filled beans, and trees presenting wilting symptoms. The national coffee sector reported losses of up to COP0.5 billion (Ocampo; Álvarez, 2017).

Coffea arabica presents a natural variability in drought conditions (Kufa; Burkhardt, 2013), and *C. canephora* presents broad genotypic and phenotypic diversity (Montagnon; Cubry; Leroy, 2012). This genetic diversity is greater in wild populations as compared with cultivated varieties (Anthony et al., 2002; Labouisse et al., 2008). The greatest genetic diversity of Cenicafe's Genetic Improvement Program lies in its Colombian Coffee Collection (CCC), which contains 568 Ethiopian introductions of *C. arabica* and 93 of *C. canephora*. Introductions of diploid species of *C. canephora* and *C. congensis* A.Froehner as well as the tetraploid species *C. arabica* were evaluated for drought tolerance, and results showed that the least affected genotypes were *C. canephora* Uganda T-3696 and *C. arabica* Catuaí (Orozco; Jaramillo, 1978). In addition, no significant decreases were observed in the Ethiopian introductions of *C. arabica* CCC238, CCC474, and CCC1147 in terms of total dry biomass, number of leaves, and leaf area when exposed to water deficit as compared with irrigation at field capacity under screenhouse conditions (Molina; Ramírez; Cortina, 2016). On the other hand, 21 coffee genotypes were evaluated at the Agronomic Institute of Paraná (IAPAR, its Portuguese acronym). Results showed that IAPAR 11260, a *C. arabica* variety containing genes of *Coffea racemosa* Lour., was the most tolerant to drought, followed by *C. arabica* Ethiopia E.368, IPR100 with genes from *Coffea liberica* Bull. ex Hiern, and IPR103 with genes from *C. canephora* (Carvalho et al., 2017).

Climate variability is expected to become increasingly severe in coming years in several of Colombia's coffee-growing areas with its subsequent effects on coffee production. This study aims to identify *Coffea* accessions that are tolerant to water deficit and whose dry biomass does not decrease significantly in water deficit conditions as compared with irrigation at field capacity, as a result, can be used as male parents to develop varieties tolerant to water stress.

2 MATERIAL AND METHODS

This study was conducted in screenhouses located at Colombia's National Coffee Research Center (Cenicafé, its Spanish acronym), located in Manizales, department of Caldas (4°58'46" N, 075°39' 25" W), with an average temperature of 23 °C to 26 °C during the experimental period. Berries were collected from 36 Ethiopian introductions of *C. arabica* (Table 1); 10 diploid accessions, one from *C. liberica* CCC1030 and nine from *C. canephora* (Table 2); 19 advanced lines of interspecific hybrids of Caturra x *C. canephora* (Table 3), together with the tall variety Typica and the short variety Caturra, both susceptible to water deficit.

The harvested berries of each accession were pulped using a JM Estrada coffee pulper with horizontal cylinders, reference Super Vencedora No. 4 ½. The enzyme Zynmucil® 5% was added to the pulped coffee and the mixture stirred for 20 min to remove the mucilage. Parchment coffee beans were washed with water and placed in a germinator, using washed river sand as substrate. After 90 days, those seedlings of each accession presenting fully expanded cotyledons were transplanted to expandable polyethylene bags containing 10 kg sandy loam Andisol soil, Chinchiná unit, with the capacity to hold 12 kg soil. Two months after transplanting, plants were fertilized using 2 g diammonium phosphate (DAP) and acclimatized in a screenhouse for six months, receiving a uniform irrigation scheme.

Forty plants from each accession were selected and, of these, 20 were randomly assigned to either of the treatments, with 20 replicates per accession and per treatment. The water storage capacity, understood as the volumetric difference between water content at field capacity and water content at permanent wilting point, was measured. Water holding at field capacity (0.03 MPa) and permanent wilting point (1.5 MPa) were also quantified. Given that water storage capacity corresponds to the maximum amount of water that a soil can store in the phase usable by plants (Veihmeyer; Hendrickson, 1927), two treatments were accordingly defined as follows: the first consisted of submitting plants to irrigation at field capacity, which corresponds to 60% soil moisture (control), and the second consisted of watering plants at 50% field capacity, which is equivalent to 30% soil moisture (water deficit). Plants were separated from the ground using 10-cm-high plastic devices and placed in a completely randomized design. After being submitted to the corresponding treatment over a 5-month period, total dry biomass was recorded as the sum of the dry biomass of leaves, stems, and roots.

To maintain soil moisture within the percentage range assigned to each treatment, the weights corresponding to both 60% moisture (soil at field capacity, control) and 30% moisture (water deficit) were determined. A Mettler MA14738 scale was used to weigh plants of each genotype and treatment twice a week. Water was subsequently added to maintain soil moisture at the above percentages. Screenhouse walls were covered with 70% polyshade to homogenize temperature conditions and solar brightness. Likewise, 20 plants were randomly selected twice a week and gravimetric soil moisture measured at a depth of 15 cm in the bag to verify that soil moisture was maintained at the percentage defined for each treatment. Information analysis consisted of determining the average, standard deviation, and 95% confidence interval of each of the variables for each accession. The Student's t test for independent samples was applied to determine if the total dry plant biomass of each accession assigned to the water deficit treatment was similar to that of plants the same accession submitted to irrigation at field capacity.

Table 1: Agronomic characteristics of Ethiopian introductions of *Coffea arabica* (Moncada; Cortina; Alarcon, 2019).

CCC	Altitude (m above sea level)	Province	Accumulated production[a]	Plant height (cm)	Empty bean	Peaberry	Supreme[b]	Cup	Fragrance/aroma
141	1750	Gojjam	9.2	178.4	13.3	16.4	35.9	5.0	Sweet
142	1800	Harar	17.3	213.4	6.5	11.5	40.8	5.5	Sweet
143	1760	Sidamo	20.0	225.0	2.7	13.0	15.8	5.0	Sweet chocolate
144	1808	Sidamo	24.3	223.1	3.3	19.1	10.0	7.0	Floral
147	1600	Sidamo	19.7	220.8	4.3	19.9	26.9	4.5	Sweet chocolate
152	1950	Shoa	18.6	210.6	6.2	13.0	24.7	4.5	Sweet chocolate
155	1610	Kaffa	18.4	169.3	4.2	11.6	51.2		
156	1610	Kaffa	22.8	170.6	6.6	17.6	22.7	7.5	Sweet
160	1610	Kaffa	28.2	171.9	5.3	14.2	29.9	4.5	Sweet
161	1610	Kaffa	30.6	176.3	8.9	16.6	35.4	7.5	Floral
1147	1700		15.6	188,8	3.2	8.6	18.6	8.0	Floral
196	1900	Illubabor	19.2	194.4	4.6	15.2	20.3	7.0	Sweet
238	1710	Kaffa	12.0	218.1	5.3	10.5	45.1	7.0	Floral
254	1200–1320	Illubabor	9.2	169,7	6.3	11,0	32.0	4.5	Bitter chocolate
258	1200–1320	Illubabor	17.4	179.1	4.8	11.1	21.1	6.0	Sweet
284	1830	Sidamo	21.4	209.4	4.7	15.1	24.0	8.0	Floral
289	1770	Kaffa	20.6	217.1	3.4	15.4	31.4		
369	1900	Illubabor	11.0	174.7	7.0	9.3	34.5	6.5	Floral
371	1900	Illubabor	10.6	161.4	5.2	13.0	59.5	5.0	Nutty
372	1900	Illubabor	12.5	201.3	7.7	13.2	17.2	7.0	Aromatic
374	1900	Illubabor	8.0	202.2	3.2	17.2	17.9	6.5	Floral
386	1900	Illubabor	4.3	162.3	3.6	14.2	30.8		
458	1240	Teppi Village	7.8	157.5	5.0	17.0	36.5	5.0	Sweet
474	1710	Kaffa	19.2	197.5	9.7	17.0	18.7	5.5	Sweet chocolate
536	1780	Gojjam	6.4	142.5	4.5	14.0	32.9		
537	1780	Gojjam			6.0	8.3	65.7		
538	1780	Gojjam	9.8	173.4	12.1	15.5	28.1	6.5	Sweet chocolate
542	1780	Gojjam	4.7	140.9	7.0	13.5	27.0		
544	1780	Gojjam	4.5	166.9	4.3	12.9	26.4	5.5	Honeyed
545	1780	Gojjam	9.5	141.3	7.1	10.5	36.8	5.5	Honeyed
548	1780	Gojjam	9.2	150.3	5.9	12.9	42.2	6.5	Floral
549	1780	Gojjam	6.9	149.4	6.4	12.5	31.2	6.0	Floral
551	1780	Gojjam	5.5	149.4	8.0	19.8	31.4	6.5	Floral
553	1780	Gojjam			4.5	12.3	52.7		
554	1780	Gojjam	7.3	154.7	5.1	10.6	34.5	6.5	Floral
555	1700	Eritrea	12.6	149.0	4.7	9.9	28.0	3.5	Bitter chocolate

[a] Kg cherry coffee berries per plant per production cycle.
[b] Coffee beans larger than 18/64 inches.

Table 2: Agronomic characteristics of diploid *Coffea* introductions (Moncada; Cortina; Alarcon, 2019).

Accessions	Genealogy	Empty	Peaberry	Supreme[a]	Accumulated production[b]	Harvests (#)	Maximum rust incidence[c]
CCC1030	*C. liberica* Excelsa						0
EA.20	*C. canephora* centro 1		9.1	78.0	61.5	5	0
EA.209	*C. canephora* Robusta L.147	1.3	2.9	71.7	75.0	5	0
EA.227	*C. canephora* Robusta BP.42	0.7	11.1	88.3	67.0	5	0
EA.229	*C. canephora* Robusta BP.42	0.3	6.7	64.1	56.5	5	0
EA.231	*C. canephora* Robusta BP.42	1.3	6.0	91.2	67.0	5	0
EA.287	*C. canephora* Laurentii		30.1	65.9	57.0	5	0
EA.342	*C. canephora* centro 1	2.0	16.1	67.3	49.5	5	0
EA.35	*C. canephora* Robusta L.147	0.3	8.3	59.4	88.0	5	0
EA.402	*C. canephora* Robusta BP.46	3.0	6.0	74.7	84.0	5	0

[a] Coffee beans larger than 18/64 inches.
[b] Kg cherry coffee berries per plant per production cycle.
[c] According to the Eskes and Braghini scale (1981).

Table 3: Agronomic characteristics of interspecific hybrid lines of *Coffea* variety Caturra x *C. canephora* (Cortina; Castro, 2015).

F3	Line	Accumulated production[a]	Plant height (cm)	Tree cup diameter (cm)	Maximum rust incidence[b]	Empty bean	Peaberry	Triangle beans	Monster beans	Supreme[c]
MEG0652.93	25	11.60	160	175	0	4	8.60	2.20	0.10	67.70
MEG0652.93	26	10.40	150	145	0	4	12.60	3.00	0.60	69.60
MEG0652.325	347	12.40	165	155	0	5	13.30	2.00	0.40	61.30
MEG0652.114	638	17.60	170	205	0	7	12.60	1.30	0.50	75.60
MEG0652.114	640	16.00	155	150	0	5	8.70	1.10	0.30	81.10
MEG0652.140	702	12.80	150	160	0	6	11.50	3.90	3.00	62.90
MEG0652.140	706	12.40	145	165	0	6	11.00	4.30	1.90	74.00
MEG0652.140	709	17.20	160	170	1	7	10.80	3.80	3.60	76.30
MEG0652.495	131	17.60	165	170	0	10	13.17	4.83	0.08	72.10
MEG0652.320	141	16.80	165	180	0	12	18.39	2.18	0.18	74.22
MEG0652.320	147	24.80	160	175	0	13	13.89	5.32	0.43	71.84
MEG0652.340	161	18.80	155	180	1	5	16.59	1.78	0.13	69.24
MEG0652.178	246	12.40	145	145	1	4	14.45	5.35	0.25	65.69
MEG0652.171	270	15.20	150	165	0	7	12.58	3.00	1.58	72.27
MEG0652.325	342	22.00	145	140	0	6	9.00	1.04	0.08	72.87
MEG0652.495	378	20.80	155	160	0	5	14.89	1.25	0.68	80.45
MEG0652.114	891	9.20	160	170	0	6	10.00	9.25	0.63	80.18
MEG0652.114	892	11.20	165	195	0	4	10.00	5.38	0.44	85.98
MEG0652.136	946	10.80	170	155	0	8	9.45	3.00	0.90	82.60
Caturra		5.20	179		8	8	10.00			44.00

[a] Kg cherry coffee berries per plant per production cycle.
[b] According to the Eskes and Toma Braghini scale (1981).
[c] Coffee beans larger than 18/64 inches.

3 RESULTS

The evaluation of CCC introductions for tolerance to water deficit indicated that 18 accessions did not significantly reduce their total dry biomass or their dry leaf, stem, and root biomass in water deficit conditions as compared with irrigation at field capacity. According to the Student's t test at a level of significance of 5%, no statistically significant differences were observed in the average total dry biomass together with dry leaf, stem, and root biomass of nine of the 36 Ethiopian introductions of *C. arabica* evaluated (CCC238, CCC254, CCC284, CCC372, CCC474, CCC536, CCC537, CCC555, CCC1147) when irrigated at field capacity with 60% soil moisture as compared with the average total biomass of plants submitted to water deficit (30% soil moisture) (Table 4, Figure 1).

In contrast, the commercial variety Típica, susceptible to water deficit, presented leaf, stem, and root dry matter values as well as total dry biomass values that were statistically lower in water deficit conditions ($P<0.001$) as compared with the treatment involving irrigation at field capacity (Table 4, Figure 1). Total dry biomass in water deficit conditions presented a 70.27% decrease in relation to the treatment involving irrigation at field capacity.

Furthermore, five diploid introductions of *C. canephora* (EA.20, EA.209, EA.227, EA.229, EA.287) and one of *C. liberica* (CCC1030) did not differ significantly in terms of total dry biomass, as well as dry leaf, stem, and root biomass in water deficit conditions as compared with irrigation at field capacity (Table 5, Figure 2). On the contrary, the total biomass of the four remaining diploid accessions (EA.231, EA.342, EA.35, EA.402) decreased under water deficit conditions as compared with irrigation at field capacity ($P<0.001$).

The total dry biomass as well as dry leaf, stem, and root biomass of advanced lines of interspecific hybrids 25, 640, and 702, obtained by the crossing of variety Caturra x *C. canephora*, did not differ statistically ($P> 0.05$) between the two test treatments: water deficit and irrigation at field capacity (Table 6, Figure 3). In contrast, variety Caturra (susceptible to water deficit) reduced not only its total dry biomass but also its leaf, stem, and root dry matter in water deficit conditions by 46.17% as compared with irrigation at field capacity (Table 6, Figure 3).

Table 4: Average, standard deviation, confidence interval and P-value of the difference in means of total dry biomass of 13-month-old plants of nine Ethiopian introductions of *Coffea arabica* and the variety Típica evaluated five months after reaching 30% soil moisture (water deficit) under screenhouse conditions at Cenicafé.

Introduction	Treatment	Average	Standard deviation	95% Confidence interval		P
CCC238	Control	33.06	6.60	30.13	35.98	0.24
	Water deficit	30.58	6.81	27.39	33.77	
CCC254	Control	21.16	9.11	16.77	25.55	0.03
	Water deficit	16.07	9.10	14.09	18.05	
CCC284	Control	28.64	7.64	24.96	32.32	0.03
	Water deficit	23.93	4.40	21.81	26.05	
CCC372	Control	22.19	6.61	19.01	25.38	0.80
	Water deficit	21.63	7.00	18.25	25.00	
CCC474	Control	25.98	3.60	24.30	27.67	0.50
	Water deficit	25.15	4.30	23.19	27.10	
CCC536	Control	17.06	8.22	13.21	20.90	0.02
	Water deficit	12.14	4.36	10.10	14.18	
CCC537	Control	26.84	10.36	21.52	32.17	0.02
	Water deficit	18.65	8.60	14.07	23.23	
CCC555	Control	18.72	5.47	15.80	21.63	0.07
	Water deficit	15.16	5.06	12.47	17.85	
CCC1147	Control	20.86	3.83	19.16	22.56	0.08
	Water deficit	18.66	4.05	16.76	20.55	
Típica	Control	27.54	12.01	21.91	33.16	0.0001
	Water deficit	8.19	2.60	6.97	9.40	

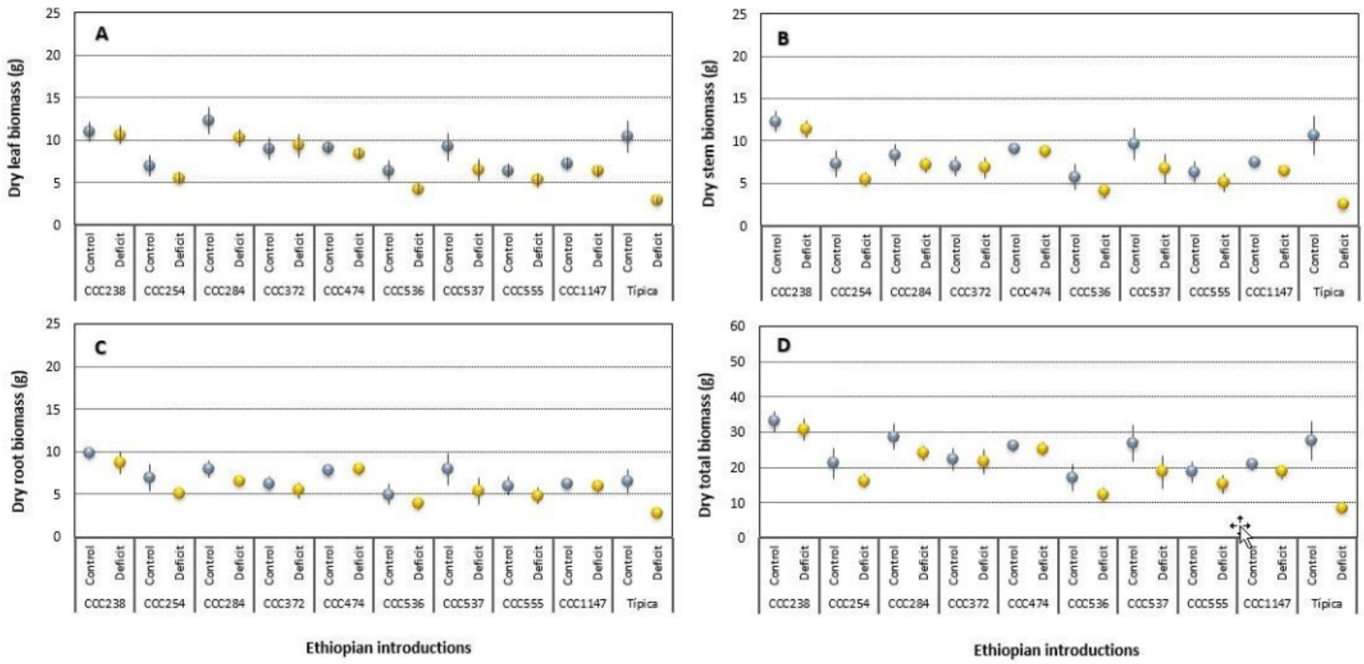

Figure 1: Dry leaf biomass (A), dry stem biomass (B), dry root biomass (C), and total dry biomass (D) of nine Ethiopian introductions of *Coffea arabica* that do not differ statistically when submitted to water deficit conditions as compared with irrigation at field capacity (control), and the coffee variety Típica.

Table 5: Average, standard deviation, confidence interval and P-value of the difference in means of total dry biomass of 13-month-old plants of six diploid accessions evaluated five months after reaching 30% soil moisture (water deficit) under screenhouse conditions at Cenicafé.

Introduction	Treatment	Average	Standard deviation	95% confidence interval		P
EA.20	Control	43.45	14.69	36.37	50.53	0.02
	Water deficit	32.53	10.30	27.57	37.50	
EA.209	Control	31.78	16.45	23.85	39.71	0.60
	Water deficit	29.36	12.20	23.65	35.07	
EA.227	Control	36.27	13.77	29.18	43.35	0.06
	Water deficit	29.04	6.45	25.83	32.24	
EA.229	Control	18.99	9.98	11.85	26.12	0.30
	Water deficit	15.21	7.53	11.69	18.73	
EA.287	Control	33.71	14.97	26.27	41.16	0.02
	Water deficit	23.05	9.56	18.28	27.82	
CCC1030	Control	24.68	16.61	15.83	33.54	0.18
	Water deficit	18.22	8.98	13.76	22.69	

4 DISCUSSION

The evaluation of 65 CCC introductions for drought tolerance indicated that 18 are promising accessions as their dry biomass did not decrease significantly in water deficit conditions as compared with irrigation at field capacity. Of these 18 accessions, nine were Ethiopian introductions of *C. arabica* (CCC238, CCC254, CCC284, CCC372, CCC474, CCC536, CCC537, CCC555, CCC1147) that showed potential to serve as male parents to develop a coffee variety tolerant to water deficit. Corroborating these findings, when three of these Ethiopian introductions (CCC238, CCC474, CCC1147) were submitted to water deficit over a 10-month period, the number of leaves, leaf area, and total dry biomass did not decrease significantly regarding the treatment involving irrigation at field capacity (Molina; Ramírez; Cortina, 2016). Two of these introductions, CCC1147 and CCC238, also presented greater water use efficiency (Molina; Ramírez; Cortina, 2016).

Similarly, the Ethiopian introduction of *C. arabica* E.368 showed great promise in view of its tolerance to drought, not differing from IAPAR 11260, which is considered as the most tolerant to drought based on the leaf wilting index (Carvalho et al., 2017).

Five diploid introductions of *C. canephora* (EA.20, EA.209, EA.227, EA.229, EA.287) and one of *C. liberica* (CCC1030) also present adaptation mechanisms to water deficit similar to drought-tolerant *C. canephora* clones that retain their leaves without reducing their total leaf area or biomass, which in turn postpones dehydration, sustains photosynthesis in the entire plant, and maintains productivity (DaMatta et al., 2003). *Coffea canephora* genotype FRT141 was also the most tolerant to drought among the six Thai robusta genotypes evaluated, presenting the highest average number of leaves, total leaf area, and total biomass (Roonprapant; Arunyanark; Chutteang, 2021). In the same way, the greater root depth in *C. canephora* allows a greater extraction of water from the soil, preserving a better internal water status (Machado Filho et al., 2021; Pinheiro et al., 2005).

In contrast, diploid accessions EA.231, EA.342, EA.35, and EA.402 decrease their biomass under water deficit conditions similar to drought-susceptible *C. canephora* clones that present a large reduction in total leaf area and biomass with the resulting inhibition of photosynthesis, which could at least partially explain the marked decrease in its production (DaMatta et al., 2003). This shows that, under water deficit conditions, the reduction in leaf area, the decrease in biomass,

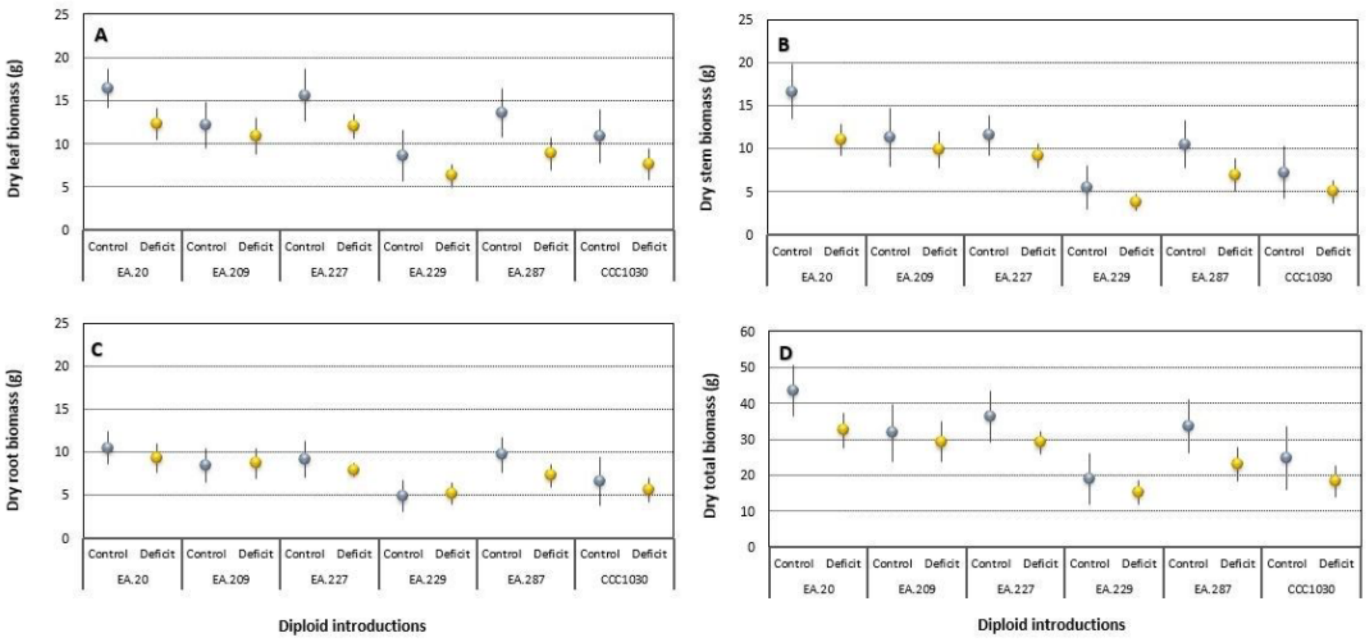

Figure 2: Dry leaf biomass (A), dry stem biomass (B), dry root biomass (C), and total dry biomass (D) of five diploid introductions of *Coffea canephora* and one accession of *C. liberica* (CCC1030) that presented biomass values that did not differ when submitted to conditions of water deficit and irrigation at field capacity (control).

Table 6: Average, standard deviation, confidence interval and P-value of the difference in means of total dry biomass of 13-month-old plants of three interspecific hybrids and the variety Caturra evaluated five months after reaching 30% soil moisture (water deficit) under screenhouse conditions at Cenicafé.

Introduction	Treatment	Average	Standard deviation	95% confidence interval		P
25	Control	17.20	9.14	12.33	22.08	0.44
	Water deficit	15.02	5.38	11.91	18.13	
640	Control	15.30	5.41	12.77	17.83	0.93
	Water deficit	15.44	3.55	13.73	17.15	
702	Control	17.72	10.16	12.31	23.14	0.20
	Water deficit	13.78	4.46	11.09	16.47	
Caturra	Control	26.16	5.16	23.68	28.65	0.0001
	Water deficit	16.30	3.75	14.55	18.06	

and the change in allocation of assimilates from leaf to root are responsible for decreased crop yield (DaMatta, 2003; Puglielli et al., 2021). Likewise, *C. canephora* clone 03, susceptible to water deficit, showed lower stem density and higher water efficiency, investing large amounts of biomass in the roots to support high water transport rates and experiencing a large decrease in carbon assimilation (Silva et al., 2013). In contrast, the higher stem density of drought-tolerant *C. canephora* clones 14 and 120 moderates the need to invest in a more robust root system (Silva et al., 2013). This not only favors aerial biomass accumulation but also photosynthesis, which in turn increases production with respect to susceptible clones. Likewise, water deficit did not affect the dry stem and root biomass of nine Ethiopian introductions of *C. arabica* (Figure 1) nor that of six diploid accessions (Figure 2), nor three interspecific hybrids (Figure 3), which favored the development of the aerial part of these genotypes identified in this study as tolerant to water deficit.

In addition, three advanced lines of interspecific hybrids obtained from the crossing of variety Caturra x *C. canephora* (25, 640, 702) outstood in terms of tolerance to water deficit, suggesting that the progeny of *C. arabica* introgressed with *C. canephora* could prove promising due to their tolerance to water deficit coming from *C. canephora*. This tolerance is similar to that observed in progeny derived from the crossing of Icatu Vermelho IAV 3851-2 (an interspecific hybrid between *C. canephora* and *C. arabica* variety Bourbon Vermelho) and Catimor UFV 1602-215 (originated from the crossing of Caturra Vermelho with the Timor hybrid), which in turn is derived from the natural hybridization between *C. arabica* and *C. canephora* (de Oliveira Santos et al., 2021). This could be due to their ability to maintain water potential through moderate water use rates, similar to drought-tolerant *C. canephora* clones that have higher WUE and better control of water loss due to transpiration attributable to stomatal closure (DaMatta et al., 2003). As a result, dehydration is postponed without reducing leaf area, photosynthesis, and total biomass values because of the activation of the ABA and nitric oxide signaling pathways (Dias et al., 2007; Marraccini et al., 2012; Silva et al., 2013). In contrast, variety Caturra (susceptible to water deficit) reduced its total biomass in water deficit conditions as compared with the irrigation at field capacity. Similarly, variety Apoatã, also susceptible to water deficit, experienced a reduction in total biomass as well as a strong decrease in carbon gain and water use (Silva et al., 2013).

The Ethiopian introductions of *C. arabica* tolerant to water deficit (Table 4) were collected in the provinces of Kaffa, Illubabor, Gojjam, Sidamo, and Eritrea (Table 1), the first three of which are located in the southwestern part of the Great Rift Valley in Ethiopia's tropical forest zone. These *C. arabica* introductions were completely isolated until the late 19th century and therefore had not been involved in any process of domestication (Meyer, 1965). As a result, they are extremely valuable to enrich the genetic base of cultivated germoplasm of *C. arabica* (Montagnon; Bouharmont, 1996; Anthony et al., 2001) for tolerance to water deficit. Because the autogamous

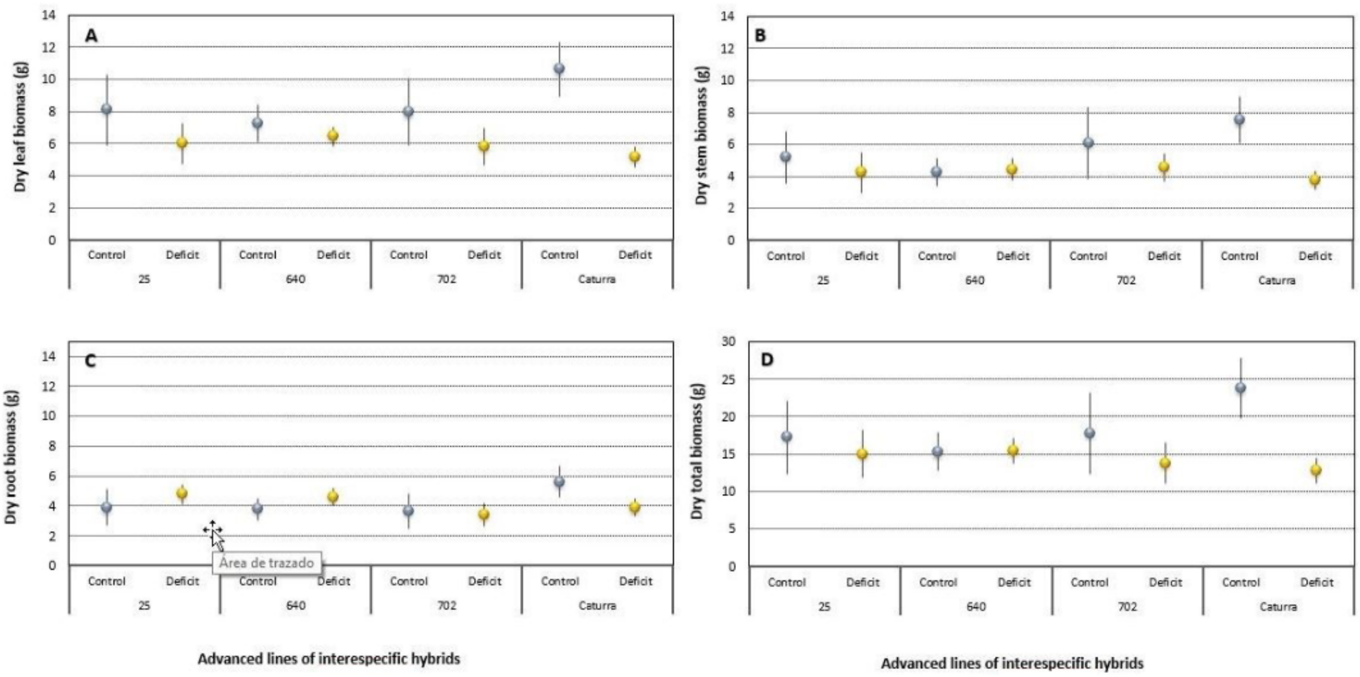

Figure 3: Dry leaf biomass (A), dry stem biomass (B), dry root biomass (C), and total dry biomass (D) of three advanced lines of interspecific hybrids of Caturra x *Coffea canephora* that present a biomass that does not differ statistically when submitted to conditions of water deficit and irrigation at field capacity (control), and the coffee variety Caturra.

nature of *C. arabica* leads to a narrow genetic base, it is difficult to find characteristics of interest, such as tolerance to abiotic stresses, in this specie. In contrast, *C. canephor*a is an allogamous species and therefore has a broad genetic base. Interspecific crosses of *C. arabica* with *C. canephora* have also been used to broaden the former's genetic base in genetic improvement efforts (Table 3). This study took advantage of the allogamous nature of *C. canephora* and the interspecific hybrids of *C. canephora* x Caturra, both highly productive and resistant to coffee rust (*Hemileia vastatrix* Berk. & Broome) (Tables 2 and 3), to find accessions tolerant to water deficit (Tables 5 and 6).

5 CONCLUSIONS

When submitted to water deficit conditions as compared with irrigation at field capacity, no significant decreases in total biomass were observed in Ethiopian introductions of *C. arabica* CCC238, CCC254, CCC284, CCC372, CCC474, CCC536, CCC537, CCC555, and CCC1147; in diploid accessions CCC1030, EA.20, EA.209, EA.227, EA.229, and EA.287; nor in the interspecific hybrids of Caturra x *C. canephora* 25, 640, and 702. Drought adaptation mechanisms allow these accessions to postpone dehydration without affecting photosynthesis or nutrient assimilation, explaining why the total biomass of these accessions did not decrease under water deficit conditions as compared with irrigation at field capacity. These accessions are promising as progenitors in endeavors to develop coffee varieties tolerant to this abiotic stress.

6 ACKNOWLEDGMENTS

Our sincere appreciation to Carlos Augusto Vera, Gilbert Rodríguez, Esteban Quintero, and Hernán Díaz for their help in collecting seeds and establishing germinators and seedbeds at the Naranjal Experiment Station as well as to soil scientist Adriana Lince for her assistance in determining soil water storage capacity and defining water deficit treatments.

7 AUTHORS' CONTRIBUTION

DM wrote the manuscript and performed the experiment, RMR review and approved the final version of the work and conducted all statistical analyses

8 REFERENCES

ANTHONY, F. et al. Genetic diversity of wild coffee (*Coffea arabica* L.) using molecular markers. **Euphytica,** 118:53-65, 2001.

ANTHONY, F. M. et al. The origin of cultivated *Coffea arabica* L. varieties revealed by AFLP and SSR markers. **Theoretical and Applied Genetics**, 104:894-900, 2002.

ARCILA, J.; JARAMILLO, A. Relación entre la humedad del suelo, la floración y el desarrollo del fruto del cafeto. **Avances Técnicos Cenicafé**, 311:1-8, 2003.

BUNN, C. et al. Multiclass classification of agro-ecological zones for Arabica coffee: an improved understanding of the impacts of climate change. **PLoS ONE**, 10:e0140490, 2015.

CARVALHO, F. G. et al. Drought tolerance in seedlings of coffee genotypes carrying genes of different species. **Coffee Science**, 12(2):156-8163, 2017.

CHESEREK, J. J.; GICHIMU, B. M. Drought and heat tolerance in coffee: a review. **International Research Journal of Agricultural Science and Soil Science**, 2:498-501, 2012.

CORTINA, H.; CASTRO, B. L. Evaluación de híbridos interespecíficos de *Coffea arabica* x *Coffea canephora* con resistencia a *Hemileia vastatrix* y *Ceratocystis colombiana*. **Revista Cenicafé**, 66(2):17-29, 2015.

DAMATTA, F. M. et al. Drought tolerance of two field-grown clones of *Coffea canephora*. **Plant Science**, 164:111-117, 2003.

DAMATTA, F. M.; RAMALHO, J. D. Impacts of drought and temperature stress on coffee physiology and production. A review. **Brazilian Journal of Plant Physiology**, 18(1):55-81, 2006.

DAVIS, A. P. et al. High extinction risk for wild coffee species and implications for coffee sector sustainability. **Science Advances**, 5(1):eaav3473, 2019.

DAVIS, A. P.; RAKOTONASOLO, F. Six new species of coffee (*Coffea*) from northern Madagascar. **Kew Bulletin**, 76:497-511, 2021.

DE OLIVEIRA SANTOS, M. et al. Photochemical efficiency correlated with candidate gene expression promote coffee drought tolerance. **Scientific Reports**, 11(1):7436, 2021.

DIAS, P. C. et al. Morphological and physiological responses of two coffee progenies to soil water availability. **Journal of Plant Physiology**, 164:1639-1647, 2007.

ESKES, A.; BRAGHINI, M. T. Assessment methods for resistance to coffee leaf rust (*Hemileia vastatrix* Berk. & Br.). **FAO Plant Protection Bulletin**, 29:56-66, 1981.

FAHAD, S. et al. Crop production under drought and heat stress: plant responses and management options. **Frontiers in Plant Science**, 8:1147, 2017.

FAOSTAT. Food and Agriculture Organization of the United Nations, Statistics Division. Available in: <http://faostat.fao.org/>. Access in: May, 18, 2022.

FEDERACIÓN NACIONAL DE CAFETEROS DE COLOMBIA. Estadísticas cafeteras. 2022a. Available in: <http://federaciondecafeteros.org/wp/estadisticas-cafeteras>. Access in: May, 18, 2022.

FEDERACIÓN NACIONAL DE CAFETEROS DE COLOMBIA. Sistema de información cafetero de Colombia. 2022b. Available in: <http://sica.cafedecolombia.com>. Access in: May, 18, 2022.

FERNANDES, F. L. et al. Economic injury level for the coffee berry borer (Coleoptera: Curculionidae: Scolytinae) using attractive traps in Brazilian coffee fields. **Journal of Economic Entomology**, 104(6):1909-1917, 2011.

GUEDES, F. A. et al. Transcriptional memory contributes to drought tolerance in coffee (*Coffea canephora*) plants. **Environmental and Experimental Botany**, 147:220-233, 2018.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE – IPCC. Climate change 2021: the physical science basis. Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change., 2021.

JARAMILLO, A.; ARCILA, J. Épocas recomendables para la siembra de cafetos. **Avances Técnicos Cenicafé**, 229:1-8, 1996.

JARAMILLO, J. et al. Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa. **PLoS ONE** 6:e24528, 2011.

JARAMILLO, J. El balance hídrico. In: FNC-Cenicafé (eds. **El clima de la caficultura en Colombia.** Manizales, Colombia: Cenicafé, 2018, 120-140p.

KUFA, T.; BURKHARDT, J. Hydraulic resistances in seedlings of *Coffea arabica* accessions under contrasting shade regimes in southwestern Ethiopia. **Journal of Agricultural Science**, 151(05):682-692, 2013.

LABOUISSE, J. P. et al. Current status of coffee (*Coffea arabica* L.) genetic resources in Ethiopia: implications for conservation. **Genetic Resources and Crop Evolution**, 55:1079-1093, 2008.

MACHADO FILHO, J.A. et al. Linking root and stem hydraulic traits to leaf physiological parameters in *Coffea canephora* clones with contrasting drought tolerance. **Journal of Plant Physiology**, 258-259:153355, 2021.

MARRACCINI, P. et al. Differentially expressed genes and proteins upon drought acclimation in tolerant and sensitive genotypes of *Coffea canephora*. **Journal of Experimental Botany**, 63:4191-4212, 2012.

MEYER, F. G. Notes on wild coffee arabica from southwestern Ethiopia, with some historical considerations. **Economy Botany**, 19:136-151. 1965.

MOLINA, D.; RAMÍREZ, V. H.; CORTINA, H. A. Comportamiento de accesiones de *Coffea arabica* sometidas a déficit de humedad del suelo. **Revista Cenicafé**, 67(1):41-54, 2016.

MONCADA, M. P.; Cortina, H.; Alarcón, R. Cup quality and yield evaluation of the Ethiopian germplasm collection of *Coffea arabica* L., **Journal of Agricultural and Rural Research,** 3(3):100-126. 2019.

MONTAGNON, C.; BOUHARMONT, P. Multivariate analysis of phenotypic diversity of *Coffea arabica*. **Genetic Resources and Crop Evolution,** 43:221-227. 1996.

MONTAGNON, C.; CUBRY, P.; LEROY, T. Amélioration génétique du caféier *Coffea canephora* Pierre: connaissances acquises, stratégies et perspectives. **Cahiers Agricultures**, 21(2-3):143-53, 2012.

OCAMPO, O.; ÁLVAREZ, L. Tendencias de la producción y el consumo de café en Colombia. **Cenes**, 36(64):139-165, 2017.

OROZCO, F. J.; JARAMILLO, A. Comportamiento de introducciones de *Coffea* sometidas a condiciones de déficit de humedad del suelo. **Revista Cenicafé**, 29:61-93, 1978.

OVALLE-RIVERA, O. et al. Projected Shifts in Coffea arabica Suitability among Major Global Producing Regions Due to Climate Change. **PLoSONE** 10(4):e0124155. 2015.

PINHEIRO, H.A. et al. Drought tolerance is associated with rooting depth and stomatal control of water use in clones of *Coffea canephora*. **Annals of Botany**, 96:101-108, 2005.

PUGLIELLI, G. et al. Global patterns of biomass allocation in woody species with different tolerances of shade and drought: evidence for multiple strategies. **New Phytologist**, 229(1):308-322, 2021.

ROONPRAPANT, P.; ARUNYANARK, A.; CHUTTEANG, C. Morphological and physiological responses to water deficit conditions of robusta coffee (*Coffea canephora*) genotypes in Thailand. **Agriculture and Natural Resources**, 55(3):473-484, 2021.

SILVA, P. E. M. et al. The functional divergence of biomass partitioning, carbon gain and water use in *Coffea canephora* in response to the water supply: implications for breeding aimed at improving drought tolerance. **Environmental and Experimental Botany**, 87:49-57, 2013.

VEIHMEYER, F. J.; HENDRICKSON, A. H. The relation of soil moisture to cultivation and plant growth. **Soil Science**, 3:498-513, 1927.