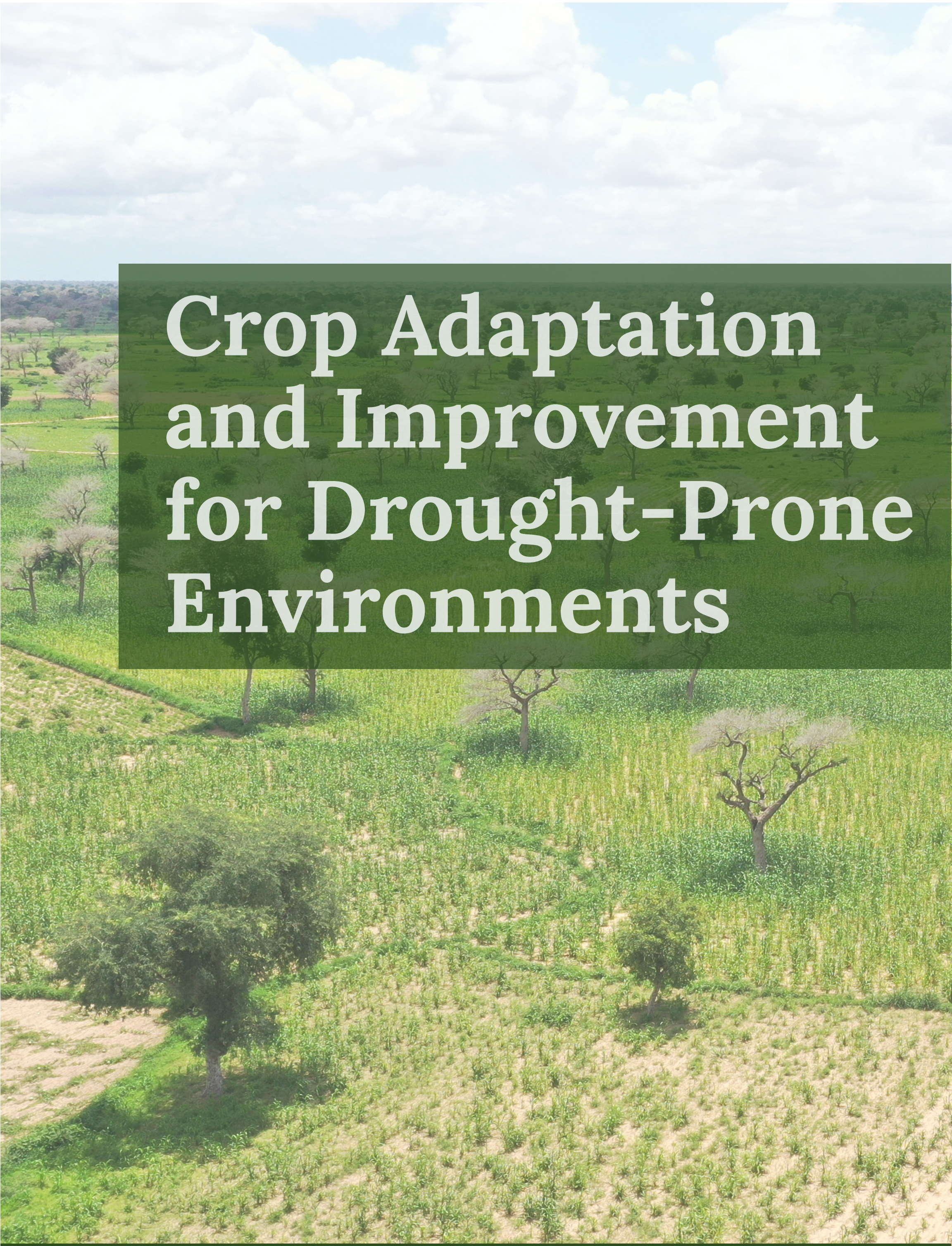

Crop Adaptation and Improvement for Drought-Prone Environments

Editors: Ndjido A. Kane, Daniel Foncéka, and Timothy J. Dalton

Cover image courtesy of: Alain Audebert (CIRAD), August 2021.

Farmers fields with millet and groundnut grown in rotation in a *Faidherbia albida* park located in the Groundnut Basin (Niakhar, Senegal).

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PART II

ADVANCED PHENOTYPING AND CROP MODELLING FOR ADAPTATION TO DRYLANDS

8. Agro-physiological Responses of 10 West Africa Sorghum Varieties to Early Water Deficit Assessed by UAV and Ground Phenotyping

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Abstract

Sorghum is a staple food for many in the Sahel. However, it often faces early-stage water deficit resulting in production decrease. Research is focusing on developing early drought tolerant varieties. This study assessed the effects of early drought stress on 10 elite varieties of West African sorghum collection tested over 2 years (2018-2019) in Bambey (Senegal). Water stress was applied by withholding irrigation 25 days after sowing for one month, followed by optimal irrigation until maturity. Soil moisture and agro-physio-morphological traits were monitored. Results showed highly significant effects of early drought stress on sorghum plants growth. The combined analysis of variance revealed highly significant differences ($P \leq 0.01$) between varieties in the different environments for most traits studied. Under water deficit, the genotypic adaptation was linked to the capacity of varieties to increase the dead leaves weight and the roots length density and to reduce photosynthesis rate, stomata conductance, and leaf transpiration. The analysis of spectral indices across water treatments revealed significant variation. However, the differential responses between varieties remained the same. Fadda (V1), Nieleni (V2), Soumba (V8) and 621B (V9) showed promising behavior under drought stress and could be suitable for further use in West Africa.

Keywords: early drought tolerance; genetic variability; root adaptation; sorghum

Introduction

Plant adaptation to water deficit is one of the key factors that will determine the severity of climate change on food production, because in the next decade, water availability will be greatly affected by climate change (Molden, 2007). Currently, agriculture uses 75% of the world's total water consumption and that is likely to increase (Molden, 2007). Food production increases at only 1.2% for the four key global crops—maize, rice, wheat, and soybean—and future demands will cause it to double (Ray et al., 2013). This is also valid for sorghum (Sorghum bicolor (L.) Moench), which is a staple food for millions of people in arid and semiarid tropical regions (Agrama et al., 2003). Its production in Africa has been estimated at 29.83 million tons from 30.54 million hectares of land (FAOSTAT, 2019).

However, the production remains unstable despite cultural practices farmers implemented to adapt and cope with the growing needs and population rise (Chaléard, 2010; Sanchez, 2002). Indeed, the latter has caused strong pressure on the arable land leading to soil depletion.

Actions to promote food security in the Sudano-Sahelian zones include the promotion of local cereal production through the identification of high-performance varieties and the breeding of new varieties. In Senegal, sorghum is one of the most important local cereals grown in the various agro-ecological zones of the country. However, climate change has increased the risk of rainfall shortage during July—the beginning of the growing season (Salack et al., 2012). This could be the cause of the low production (291.171 tons in 2019) (DAPSA, 2019). Early-stage water deficit is experimented with in many research studies by withholding water supply at the beginning of the crop growth cycle, about 3 weeks after germination, for 3 to 4 weeks (Debieu et al., 2018; Qazi et al., 2014; Zegada-Lizarazu & Monti, 2013). This causes a decrease in leaf appearance, transpiration, and photosynthesis through leaf senescence (Craufurd & Peacock, 1993; Dwivedi et al., 2008; Tari et al., 2013). The combined effects of drought and rewatering are still not well-known, especially regarding sorghum. The ability to recover from early water deficit during rewatering can explain in some cases the yield difference between varieties at harvest (Zegada-Lizarazu et al., 2013). The drought recovery index (DRI) represents rewatering-induced recovery of the growth traits related to biomass, height, etc., and would be suitable for investigating drought tolerance. According to Perrier et al., (2017), recovery capacity is an important trait for future phenotyping, genetic and breeding studies while its process and genotypic variability are poorly understood. Late maturity genotypes appeared to be more tolerant to early drought because the stress occurs before the panicle initiation phase, when plants have more ability to recover after rewatering. However, these genotypes no longer suit the farming systems of semiarid regions because of the shortened rainy season. Thus, the solution would be to identify improved short-cycle varieties capable of adapting to early season water stress. This requires a characterization of sorghum behavior under early season water stress and the identification of relevant selection criteria to facilitate the decision on the choice of varieties for cultivation and breeding programs.

Root response is of prime importance to crop productivity under drought stress. This is because the root size, architecture, and distribution determine the ability of plants to access and take up the water for proper physiological functioning of shoots (Henry, 2013; Taiwo et al., 2020). Sorghum's ability to adapt to water shortage is also due to its root system, which can extend into the deep soil layers. The investigation of this trait through the measurement of root length density (RLD) trait revealed useful (Masi & Maranville, 1998). Researchers have been working to identify specific root traits targeted for plant improvement under drought and limited nutrients conditions (Comas et al., 2013; Girma et al., 2020; Lynch et al., 2014). Recently, greater focus was given to root system architecture, especially the RLD distribution in the soil, which is a key factor for water and nutrient uptake (Chopart et al., 2008; Gregory, 2006). However, field assessment of RLD is not obvious. Among other methods, the trench profile method for mapping root intersection in a soil profile was identified as more efficient and feasible to provide information on roots distribution (Böhm, 1976; Chopart et al., 2008; Tardieu, 1988).

Another method investigated in this study is the use of vegetation indices (VIs) calculated from Unmanned Aerial Vehicle (UAV) multispectral images to phenotype sorghum varieties under drought. Previous findings have promoted VIs related to normalized difference vegetation index (NDVI) as an important multi spectral index to track the agro-physiological dynamics of key traits such as biomass, leaf area index (LAI), yield, etc. (Foster et al., 2017; Magney et al., 2016; Samborski et al., 2015). However, breeders are not aware and have less understanding about the application of the different reflectance bands ratio on monitoring crops development and adaptation. Higher level of NDVI is associated with faster growth rate, higher biomass accumulation during the vegetative stage, and a longer grain filling period by delaying leaf senescence during the ripening phase thereby increasing yield (Babar et al., 2006).

The objectives of this study were to investigate the effects of early water deficit in sorghum to determine the main adaptation mechanisms and simultaneously highlight an interesting method and criteria for the agro-physiological characterization of sorghum in water deficit conditions.

Material and Methods

1. Plant Material

The plant material used in this study consisted of 10 elite varieties of sorghum from Senegal, Mali, and Nigeria (West Africa) (see Table 1). They differ in terms of phenology (from 90 days to 128 days cycle duration), plant architecture (120 cm to 450 cm height), response to inputs (hybrid vs. open pollinated varieties caudatum or guinea), and yield (2 t/ha to 4.5 t/ha) (Dembele et al., 2020). These varieties are widely cultivated by the farmers because of their adaptability and agronomic characteristics (Dembele et al., 2021; Gano et al., 2021; Ndiaye et al., 2018; Ndiaye et al., 2019).

Table 1
Characteristics of the Varieties Studied

Variety	Code	Type	Cycle (days)	Height (cm)	Potential yield (t/ha)	Panicle form	Photoperiod-sensitivity	Isohyet (mm)	Origin
Fadda	V1	Guinea (hybrid)	128	200-300	4.5	noncompact	mean	700-1000	Mali
NIELENI	V2	Guinea (hybrid)	115	300	4	semicompact	low	700-800	Mali
IS15401	V3	Guinea-Caudatum	115	400-450	2	semicompact	high	900-1200	Mali
PABLO	V4	Guinea (hybrid)	125	400	4	noncompact	mean	700-1000	Mali
CSM63E	V5	Guinea	90	400	2	noncompact	low	600-1000	Mali
SK5912	V6	Caudatum	170	200	2.5-3.5	semicompact	high	700-900	Nigeria
GRINKAN	V7	Caudatum	90	120	4	semicompact	non	500-800	Mali
SOUMBA	V8	Caudatum	115	250	2.5	semicompact	low	600-1000	Mali
621B	V9	Caudatum	105	175	2.5-3	semicompact	non	600-900	Senegal
F2-20	V10	Caudatum	110	210	3-5.3	semicompact	low	600-900	Senegal

2. Methods

2.1 Trial Conditions

Trials were conducted at Bambey (14°42’N; 16°28’W) (Senegal) in the Centre National de la Recherche Agronomique (CNRA) on a sandy soil (sand = 94.2%, silt = 3.5%, clay = 2.3%) with a previous cowpea crop. Three trials were carried out between 2018 and 2019 during the dry seasons, which allowed control of the water supply by irrigation. The experimental design is a randomized complete block design, with irrigation as the main factor, and varieties randomized in three replications in each main block. The two water treatments (well-watered [ww] and drought stress [ds]) were placed 10 m apart to avoid involuntary irrigation. A sprinkler method of water supply was provided twice weekly with 25 mm per irrigation (50 mm per week) until physiological maturity. The amount of irrigated water was calculated to cover the weekly average evapotranspiration of sorghum that varied between 25 mm to 37 mm (see Figure 1D). One irrigation was applied before and after sowing to promote good seedling emergence. Fertilizers were applied after sowing and at 21 days after sowing (DAS) as NPK and urea respectively following standard recommendation (i.e., 150 kg ha^{-1} of NPK [15-15-15] and 100 kg ha^{-1} of urea). Water stress was applied by withholding irrigation in the drought stress environment for 1 month from the 25^{th} DAS.

2.2 Weather Conditions

Figure 1 shows the climate conditions (vapor pressure deficit [VPD], solar radiation, relative humidity, and temperature) during both experiments. There was a high evaporative demand during these dry seasons as shown by the VPD data that reached 5 KPa during the day. The dry season is characterized by high temperature (above 30°c) and high solar radiation (800 $w.m^{-2}$) during the day. These climate conditions are representative of the dry season, allowing control over water supply.

Figure 1

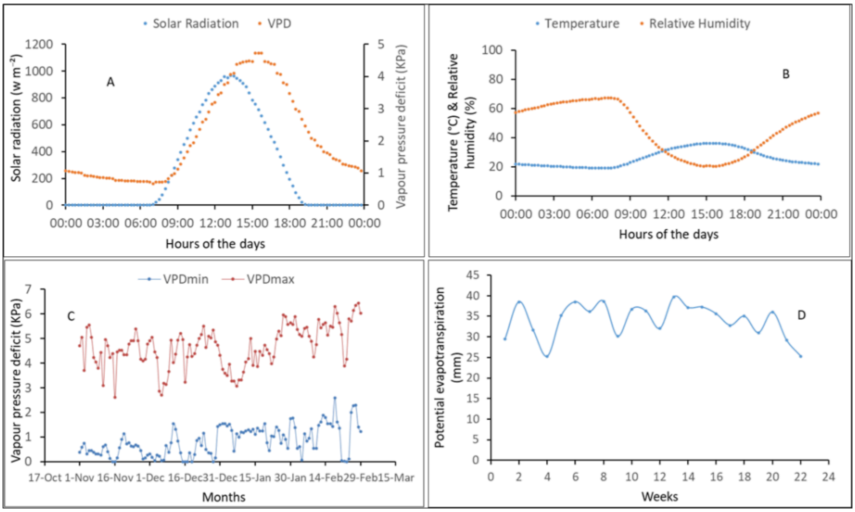

Figure 1 – Climate Conditions During the Experiments in Bambey in 2018 and 2019.

Notes. (A) Daily averages of vapor pressure deficit (VPD) and solar radiation; (B) Temperature and relative humidity; (C) Minimum and maximum VPD; (D) Potential evapotranspiration. Although climate conditions were measured in both years, only representative annual graphics were presented. (A) and (B) were recorded during 2018 experiment and (C) and (D) during the 2019 experiment.

2.3 Monitoring Water Stress

Water stress in the field was monitored by measuring the volumetric soil moisture (Diviner 2000, Sentek Pty Ltd) once a week during the irrigated period and twice a week during the stress period to assess the fraction of transpirable soil water (FTSW) (Debieu et al., 2018; Sinclair & Ludlow, 1986). Diviner probe tubes of 1.6 m length were used to record water stock at every 10 cm of depth. In this work, a total of 1.6 m depth water stock was considered to assess the FTSW as this depth represents the sorghum's root activity zone. Soil moisture measurements allowed us to follow the level of stress down to FTSW = 0.3 at the end of the stress period. The average of the three most contrasted varieties was used to evaluate the general trend. We also monitored the predawn leaf water potential once a week using the pressure chamber (PMS Instrument Co., Corvallis, Oregon, USA) according to the protocol of Peyrano et al. (1997). The plant's water potential was measured before sunrise, when there is a balance between plant and soil for water potential.

2.4 Assessment of Agro-physiological Traits

Plants' agro-physiological traits—such as number of leaves appeared (NLA) and plant height after stress (PHS)—were measured on three tagged plants per plot. The photosynthesis rate (Pn), leaf temperature (Tleaf), transpiration (Tr), and stomata conductance (C) were measured on the last ligulate leaf using the CI340 handheld photosynthesis system (CID Bio-science, USA). Biomass production was evaluated by estimating plant dry weight (DWP) and dead leaves weight (DLW) using six plants per plot at seven different dates (before the stress, at the end of the stress, and after recovery [2 weeks after rewatering]). At physiological maturity, grain yield, plant height (PHT) and straw dry biomass (SDW) were measured. The specific leaf area (SLA) was calculated as the ratio between plant leaf area and biomass.

Moreover, other morphological traits were measured weekly during drone flights on three randomly tagged plants per plot, from crop emergence (25 DAS) to flowering-maturity stage (89 DAS). Seven sampling weeks' data were used for LAI and biomass. LAI was measured using the SunScan septometer (Delta-T Devices, Cambridge, England). Nondestructive measurements (LAI) were performed just before UAV flights. Plants were sampled, dried outdoors for 2 weeks, and oven-dried for 3 days before biomass measurements were taken using ad-venturer pro precision balance (OHAUS Corporation, Pine Brook, New Jersey, NJ, USA).

To better study the recovery performance and classify varieties, we introduce a new parameter that we have named the DRI. The DRI represents the relative recovery of the growth traits (NLA, PHS, DWP, Pn) after a freely defined time of drought stress followed by rewatering. This approach was inspired by the drought factor index (DFI) used by Strauss et al. (2006) for the detection of dark chilling tolerance in soybean genotypes and by Oukarroum et al., (2007) for probing the response of barley cultivars under drought stress conditions. DRI was calculated by applying the formula:

$$\mathbf{DRI} = \log A + 2 \log B \quad (1)$$

in which A is the relative trait measured at the end of the drought period and B is the relative trait measured 2 weeks after rewatering. The relative trait is calculated as trait drought over trait control. The principle of the DRI is that recovery efficiencies should play an important role on the production capacity of some genotypes. Varieties with DRI near to zero have good recovery and varieties with DRI around -1 have bad recovery index (Oukarroum et al., 2007).

2.5 Roots Phenotyping

Root measurements were done on two tagged plants per plot. We used the described methods, to count the number of adventitious roots and estimate RLD from intersections between the roots and the face of a soil trench profile (Chopart et al., 2008; Dusserre et al., 2009; Faye et al., 2019). The trench profiles were dug perpendicular to the rows of seedlings and at two distances (20 cm then 10 cm) from the plant stem. Iron grids of 60 cm length by 30 cm width, in relation to the spacing between rows and between plants, were used to count root impacts. Square meshes of 10 cm side length were made inside the grids to facilitate the measurement of the number of impacts. At the end of the stress period, the plants were dug up for additional measurements on the tilling tray, such as the number of adventitious roots.

2.6 UAV Data Capture and Image Analyses

Time series flights were done at the altitude of 25 m and a constant speed of 2.2 $m.s^{-1}$ with the hexacopter drone (FeHexaCopterV2, MikroKopter Company, Moormerland, Germany). Seven UAV weekly flight data, from emergence to maturity, were recorded. Nine grey colored ground control points (GCPs) were uniformly distributed over the entire field area with fixed position for all the flights throughout the experiment. These were surveyed using Precis BX305 Real Time Kinematics (RTK) GNSS unit (Tersus GNSS Inc., Shanghai, China). The GCPs were made of painted PVC disks of 60 cm diameter where the central disk of 40 cm diameter was 20% gray level and the outer disk 60% gray level color. These gray levels were selected to avoid saturation and allow automatic target detection on the images. The

UAV system, equipped with six motors, can perform user-defined waypoint flights with a differential global navigation satellite system (GNSS) receiver. The UAV support software (Mikrokopter tools, Mikrokopter Company, Moormerland, Germany) that implements the flight plan also monitors the flight and records information such as drone position. The flight was performed with an RGB ILCE-6000 digital camera (Sony Corporation, New York, NY, USA) with a 6000×4000-pixel sensor equipped with a lens of 60 mm focal length. To minimize the blurring effect and noise in the images, the camera was set on speed priority (1/1250 sec) and auto ISO mode. Another flight was performed with an Airphen multispectral camera (hiphen, Avignon, France, https://www.hiphen-plant.com/) equipped with a lens of 8 mm focal length and acquiring 1280×960-pixel images. The Airphen consists of six individual cameras equipped with filters centered on 450 nm, 530 nm, 560 nm, 675 nm, 730 nm, and 850 nm, with a spectral resolution of 10 nm. For each camera (RGB and MS), the flight lasted about 15 minutes with a break of approximately 10 minutes in between to prepare the second flight. The cameras captured images at 1-second intervals and recorded them in JPG and Tiff format on the SD memory card. The drone did round trips spaced by 4 m that allowed a side and forward overlapping fraction of 0.75. To reduce the effects of ambient light conditions, such as plant shadow that can greatly affect spectral measures especially between rows at maturity stages, the flights were limited to clear and cloudless days between 10:00 a.m. and 12:00 a.m. UTC.

An automatic image-processing pipeline was designed to generate radiometrically calibrated and geometrically corrected multiband orthoimages using Agisoft PhotoScan digital photogrametric software version 1.4.0 (Agisoft LLC, St. Petersburg, Russia, https://www.agisoft.com/downloads/installer) (see Part 2 Chapter 1, Mbaye et al. in this book). Radiometric calibration included automatic correction of vignetting effects (Iqbal et al., 2018). Real reflectances were computed using a reference target positioned to the ground during UAV flights. This target was previously spectrally characterized in controlled conditions. Geometric correction involved firstly, multiband coregistration to modify and adjust the images' coordinate system to decrease geometric distortions and make pixels in different pictures coincide with the corresponding map-grid points. The coregistration process was based upon the internal GNSS from raw image metadata. Orthorectification was then performed using GCPs to increase the accuracy of the generated orthoimage. As Agisoft Photoscan manages multilayer images, we used the 450 nm band for tie point searching. For a better plots segmentation, we uploaded the RGB orthoimage in QGIS (Geographical Information SYSTEMS, version 3.10.0, QGIS Development Team, open source 2019, https://www.qgis.org/fr/site/forusers/download.html) and designed the plots boundaries. The created shapefile with the GNSS coordinates of each plot was exported as spatial vector data. The extraction of the average values of the varieties' vegetation index in each plot was performed according to the GNSS coordinates of plots, extracted on QGIS and MS orthoimage. The computation was performed using R software (version 3.6.0) libraries (sf, raster, rgdal, RSToolbox and uavRst) (R Core Team, 2020). Four vegetation indices (NDVI, CTVI, MSAVI2 and SR) were used to estimate LAI and biomass during the dry seasons of 2018 and 2019. These vegetation indices are single values computed by grid calculation.

They are invariant to the difference in illumination conditions, slope, seasons, etc. They represent a quick way to distinguish green leaves from other objects and to estimate the relative biomass present on the image, therefore, distinguishing stressed vegetation from nonstressed (Li et al., 2018; Shi et al., 2016; Steven et al., 2015; Zhang et al., 2017).

2.7 Statistical Analyses

The raw data were analyzed using R software version 3.6.0 (www.r-project.org). An analysis of variance was performed for each environment (ww and ds) to verify statistical differences between varieties. Subsequently, a combined analysis of variance was performed to test the effects of water stress and years on varieties. The homogeneity between residual variances was tested using Bartlett's test (Bartlett, 1937). RLD was modeled on the basis of measurements of root intersections density (RID) on a vertical perpendicular plane within a sorghum row because this method is most commonly used for studying roots in a soil profile. Relationships between RLD and RID were evaluated taking the slope, the standard error of the slope (SE), the intercept, and the regression (r^2) into account. Ordinary least squares linear regression models were applied. Regression models were developed to predict LAI and biomass using vegetation indices. The performance of regression models in estimating LAI and biomass were evaluated by calculating the root mean squared error (RMSE), the coefficient of determination (r^2) and p-values at the probability level of 0.05.

Results

1. Water Stress

During the irrigation period, FTSW and predawn leaf water potential showed a very low variation and revolved around 0.7 and -1.5 bars, respectively (see Figure 2). However, when the plots in the ds treatment were let to dry down, FTSW and predawn leaf water potential decreased progressively and reached 0.3 and -5 bars respectively, showing an effective drought stress experience that occurred between 35 DAS and 55 DAS. Thereafter, after resuming irrigation, these parameters increased again and stabilized around the initial values with a slight drop (0.6 and -2 bars for FTSW and predawn leaf water potential, respectively).

Figure 2

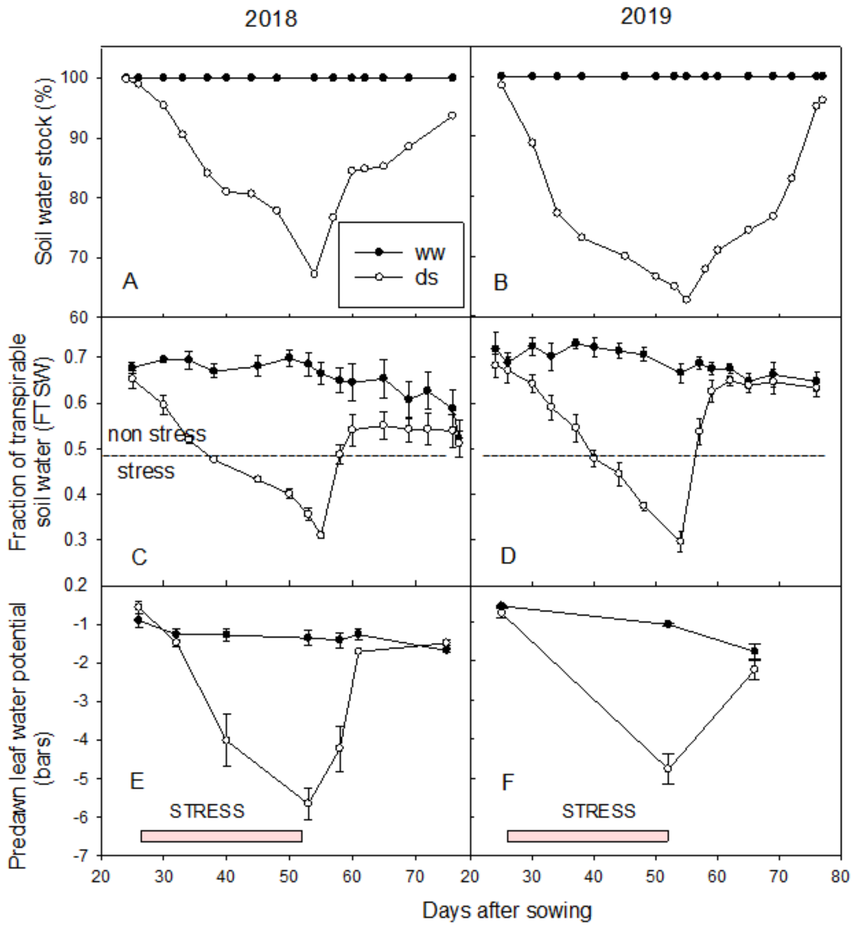

Figure 2 – Monitoring of Water Stress Parameters in Well-watered (ww) and Drought Stress (ds) Treatments

Notes. (A) Evolution of soil moisture stock (%) in 2018 and (B) in 2019; (C) Fraction of transpirable soil water in 2018 and (D) in 2019; (E) Predawn leaf water potential (bar) in 2018 and (F) in 2019.

2. Effects of Early Water Deficit on Growth, Recovery, and Yield

Table 2 presents the effects of water deficit on agro-physiological traits assessed in the experiments. The results showed highly significant differences ($P \leq 0.01$) between the different environments for all the characters under study. The early water deficit led to a reduction of leaf appearance (NLA) (-9.18% in 2018 and -6.75% in 2019); PHS (-16.37% and -48.99%); Pn (-12.45% and -27.75%); C (-18.37% and -35.32%); and Tr (-26.37% and -25.92%). After maturity and harvest, we observed a decrease in yield (-22.78% and – 28.15%), SDW (-18.25% and -27.79%) and PHT (-15.01% and -23.23%). However, we noticed an increase in the DLW (+43.29% and +15.10%) and Tleaf (+1.29% and +7.64%).

Table 2

Average Performance and Statistical Parameters of Some Agro-, Physio- and Morphological Traits of Sorghum Genotypes Under Well-watered (ww) and Drought Stress (ds) Conditions of 2018 and 2019 Field Trials

	Year 2018				**Year 2019**			
Traits	Mean ww	Mean ds	ΔWS	Signif.	Mean ww	Mean ds	ΔWS	Signif.
NLA	15.33a	13.92b	-9.18	***	15.30a	14.26b	-6.75	***
PHS	143.89a	120.33b	-16.4	***	130.55a	66.59b	-49	***
DLW	13.65b	19.56a	43.29	***	14.22b	16.37a	15.1	***
PHT	174.83a	148.58b	-15	***	165.75a	127.24b	-23.2	***
SDW	453.38a	370.61b	-18.3	***	427.35a	308.60b	-27.8	***
Yield	3271.85a	2526.21b	-22.8	***	2419.84a	1738.64b	-28.2	***
Pn	39.32a	34.43b	-12.5	***	41.38a	29.90b	-27.8	***
C	184.94a	150.97b	-18.4	***	179.14a	115.88b	-35.3	***
Tr	7.43a	5.47b	-26.4	***	7.04a	5.22b	-25.9	***
Tleaf	39.02b	39.53a	1.29	**	39.16b	42.15a	7.64	***

NLA: number of leaves appeared; PHS: plant height after stress (cm); DLW: dead leaves weight (g); PHT: plant height (cm); SDW: Straw dry weight (g); Yield: grain yield (kg/ha); Pn: photosynthesis rate; C: stomata conductance; Tr: leaf transpiration; Tleaf: leaf temperature; Signif: significance at p:s 0.001 (***) and p:s 0.01 (**); ΔWS: delta water stress (%). For a given trait, numbers followed by the same letters are not significantly different between water treatments.

Figure 3 represents the monitoring of C, SLA per plant, plant height, NLA on the main stem. DWP, and Pn of varieties under both conditions (ww and ds). The results showed that the number of leaves on the main stem, plant height, and dry weight per plant gradually increased in a similar way between varieties, but the advent of water stress induced a drop. These results indicated that water stress causes significant reduction in biomass production and shoots growth in sorghum. The SLA of the plant, which reflects the thickness of the leaves, the C, and the (Pn) initially increased to reach their maximum at the 30th DAS, before gradually decreasing until maturity. In the water-stressed environment, the drop in SLA, C, and Pn was greater than in the nonstressed conditions. After the end of the stress period, these traits rebounded but without recovering to the SLA, C, and Pn values of the nonstressed environment. In terms of height and biomass, the varieties have all lost pace despite the high plasticity found in sorghum.

Figure 3

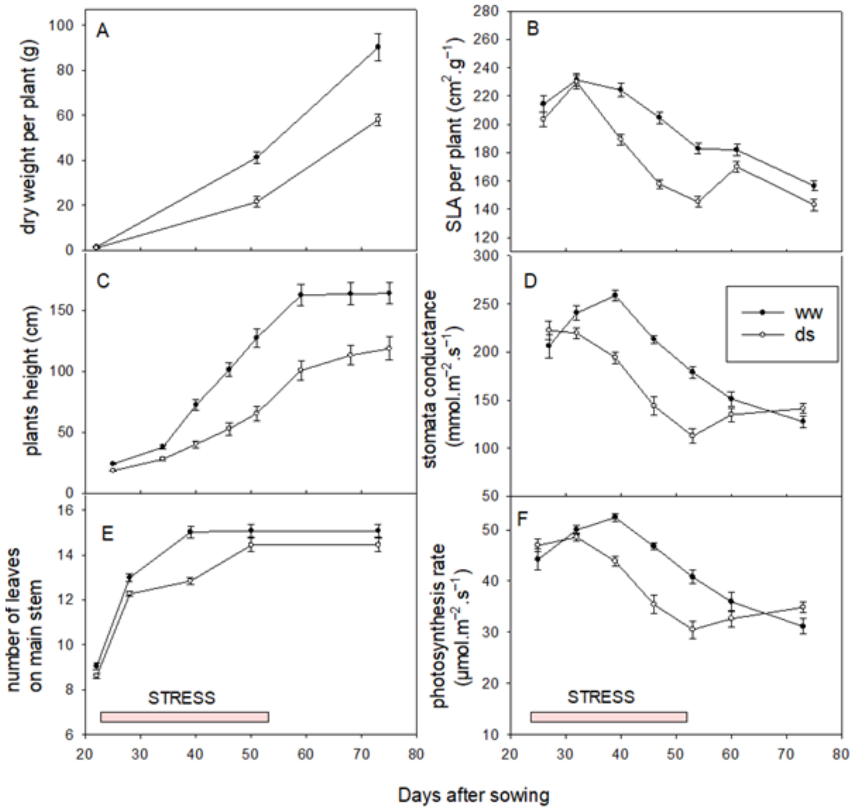

Figure 3 – Evolution of Agro-physiological Traits of Sorghum Varieties Under Well-watered (22) and Drought Stress (ds) Conditions

Note. (A) Dry weight per plant, (B) Specific leaf area (SLA) per plant, (C) Plant height, (D) Stomata conductance, (E) Number of leaves, (F) Photosynthesis rate

Sorghum varieties that exhibited the smallest values of DRI had more problems recovering. We noted that varieties had good recovery in the NLA and Pn with a DRI of -0.11 and -0.04 respectively. However, varieties' recovery on PHS and the DWP was more difficult with a DRI of -0.62 and -0.65 respectively (see Table 3). The results indicated a best recovery on plant height and dry weight for the variety V3 and V1 respectively; varieties V4, V5, and V6 revealed the worst recovery on the same traits.

Table 3
Drought Recovery Index of Sorghum Varieties on Some Growth Trait

Drought Recovery Index (DRI)				
Varieties	**NLA**	**PHS**	**DWP**	**Pn**
V1	-0.04	-0.54	-0.32	-0.22
V2	-0.1	-0.43	-0.6	-0.24
V3	-0.12	-0.33	-0.75	-0.08
V4	-0.13	-0.81	-0.98	0.07
V5	-0.1	-0.68	-0.64	0.35
V6	-0.09	-0.8	-0.97	-0.16
V7	-0.13	-0.55	-0.93	-0.05
V8	-0.11	-0.77	-0.57	0.12
V9	-0.12	-0.62	-0.44	-0.18
V10	-0.12	-0.69	-0.32	0
MEAN	-0.11	-0.62	-0.65	-0.04

NLA: number of leaves appeared; PHS: plant height after stress; DWP: dry weight per plant; Pn: photosynthesis rate

3. Adaptation Responses to Early Water Deficit

The combined analysis of variance revealed highly significant differences ($P \leq 0.05$) between varieties; environment; and the interactions between variety (V), environment (E), and year (Y), (V*E, V*Y, E*Y and V*E*Y) (see Table 4). Variety V7 showed the smallest number of leaves and PHS; V6 and V3 recorded respectively the highest values for these traits. Varieties V8 and V4 had the highest DLW in both years; V1, V6, and V9 recorded the smallest values. At harvest, variety V5 exhibited the highest plant height and SDW but the lowest grain yield. V7 and V9 exhibited the lowest plant height and SDW respectively. V1 and V10 recorded the highest grain yield under ww conditions in 2019 and 2018 respectively; V1 and V9 recorded the highest one under ds conditions in 2019 and 2018 respectively.

Table 4a
Performance of 10 Sorghum Varieties Under Two Water Treatments (Well-watered and Drought Stress) for Agro-morphological Traits Measured During 2018 and 2019 Field Trials

		NLA		PHS		DLW	
	V	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**
Year 2018	**V1**	14.6cd	13.5bc	133.7bc	111.7bcd	5.7e	13.9cd
	V2	15.3bc	13.6bc	125.7bc	101.6bcd	16.8ab	28.7a
	V3	15.5abc	13.2bc	204.3a	179.3a	12.6bcd	25.8a
	V4	15.5abc	13.8bc	200.6a	137.5b	10.7cde	17.3bc
	V5	15.0bc	13.5bc	186.3a	193.5a	6.0e	16.6bc
	V6	16.6a	15.9a	108.5cd	91.2cd	7.8de	9.9de
	V7	13.5d	12.4c	92.5d	86.2cd	14.2bc	19.2b
	V8	16.0ab	14.4ab	147.5b	111.8bcd	22.4a	26.9a
	V9	15.7abc	14.9ab	98.4d	74.0d	18.3ab	8.6e
	V10	15.1bc	13.8bc	141.0b	116.1bc	21.4a	28.3a
	Grand mean	15.3a	13.9b	143.8a	120.3b	13.6b	19.5a
	ANOVA						
	V	***	***	***	***	***	***
	E	***		***		***	
	V×E	ns		**		***	
Year 2019	**V1**	15.7ab	13.7a	120.4a	77.5a	13.7d	15.1e
	V2	16.5a	14.2a	140.6a	83.5a	14.9ab	16abcd
	V3	15.0ab	13.8a	163.1a	103.1a	11.9f	15.7de
	V4	15.2ab	14.3a	107.3a	38.3a	15.3a	16.1cd
	V5	15.5ab	14.3a	154.6a	68.5a	14.8ab	16.3bcd
	V6	16.0a	15.3a	107.1a	60.8a	12.6e	16.1cd
	V7	13.5b	14.1a	106.5a	55.3a	14.5bc	16abcd
	V8	15.8ab	14.4a	124.5a	49.0a	15.1ab	17.2a
	V9	15.1ab	14.4a	99.4a	53.5a	15.0ab	17.1ab
	V10	14.3ab	13.7a	149.4a	66.3a	14.0cd	16.7abc
	Grand mean	15.3a	14.2b	130.5a	66.5b	14.2b	16.3a
	ANOVA						

		NLA		PHS		DLW	
	V	ww	ds	ww	ds	ww	ds
	V	*	ns	ns	ns	***	***
	E	***		***		***	
	V×E	ns		ns		***	
Both years	Y	ns		***		***	
	V×Y	*		***		***	
	E×Y	ns		***		***	
	V×E×Y	ns		**		*	

Table 4b

		PHT		SDW		YIELD	
	V	ww	ds	ww	ds	ww	ds
Year 2018	V1	172.5cd	148.9cd	427.6bc	358.7abc	4183.4abc	3182.3b
	V2	162.8d	140.4cde	470.2abc	349.3abc	3715.9d	3359.3b
	V3	191.2bc	193.6ab	498.7ab	409.0abc	2001.5e	1817.6de
	V4	205.6b	161.3bc	530.0ab	449.8ab	1606.4ef	1540.3e
	V5	235.3a	215.6a	603.2a	461.4a	1473.1f	1168f
	V6	159.8d	133.6cde	408.0bc	424.4ab	3926abcd	2598.3c
	V7	127.2e	108.9e	315.0c	294.5bc	3812.1cd	2006.9d
	V8	168.1d	126.0de	496.8ab	339.9abc	3922bcd	3132.8b
	V9	152.2d	117.1de	321.5c	259.3c	4246.0ab	3851.7a
	V10	169.3cd	140.0cde	451.0abc	359.3abc	4349.3a	2643.02c
	Grand mean	174.8a	148.5b	453.3a	370.6b	3271.85a	2526.21b

		PHT		SDW		YIELD	
	V	ww	ds	ww	ds	ww	ds
	ANOVA						
	V	***	***	***	**	***	***
	E	***		***		***	
	V×E	*		Ns		***	
Year 2019	V1	173.2cd	127abcd	494.2bc	377.3abc	3876.8a	2424a
	V2	149.4de	120.1bcd	404.5bcd	259.0bc	2127.7cd	2070.3abc
	V3	216.7ab	170.4abc	329.6cd	323.0abc	1886.4d	1752.5bc
	V4	204.6bc	183.2ab	791.2a	399.4ab	1233.9e	1124.5de
	V5	250.8a	198.2a	564.5b	428.4a	771.2f	817.4e
	V6	137.9ef	88.4d	413.2bcd	274.0abc	3429.2ab	1582bcd
	V7	109.2f	93.4d	380.8bcd	246.5c	3166.7b	2027.6abc
	V8	143def	106.1cd	330.4cd	267.8abc	2514.8c	2087.6ab
	V9	131.4ef	101.8cd	303.7d	272.0abc	2105.5cd	2037abc
	V10	140def	102.6cd	382.6bcd	278.3abc	3085.8b	1462.9cd
	Grand mean	165.7a	127.2b	427.3a	308.6b	2419.84a	1738.64b
	ANOVA						
	V	***	***	***	**	***	***
	E	***		***		***	
	V×E	*		**		***	
Both years	Y	***		***		***	
	V×Y	***		**		***	
	E×Y	ns		**		*	
	V×E×Y	ns		ns		***	

ww: well-watered; ds: drought stress; NLA: number of leaves appeared; PHS: plant height after stress; DLW: dead leaves weight; PHT: plant height at harvest; SDW: Straw dry weight; Yield: grain yield; V: variety; E: environment; Y: year; *** significant at $p = 0.001$; ** significant at $p = 0.01$; * significant at $p = 0.05$; ns: not significant. The means with the same letters are not significantly different. The bold values indicate the highest and lowest value measured.

Physiological traits like photosynthesis rate, stomata conductance, leaf transpiration, and leaf temperature revealed a wide range of genetic variability among the varieties under both ww and ds conditions (see Table 5). The effects of variety, environment, and their interaction (V× E) were highly significant in both years. Under ww conditions, variety V1 recorded the highest photosynthesis rate, stomata conductance, and leaf transpiration; V5, V9, and V2 recorded respectively the lowest values for the same traits in 2018. However, the occurrence of drought stress induced various responses in these varieties. Variety V10 recorded the lowest photosynthesis rate in 2018 but the highest rate in 2019, showing variation in the behavior of this variety from year to year. Overall, a decrease of photosynthesis rate, stomata conductance, and leaf transpiration—and an increase of leaf temperature—were the physiological responses of the studied varieties to early water deficit (see Table 5).

Table 5

Performance of 10 Sorghum Varieties Under Two Water Treatments (well-watered and drought stress) for Physiological Traits Measured During 2018 and 2019 Field Trials

		Pn		C		Tr		Tleaf	
	V	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**
Year 2018	**V1**	43.14a	31.92abc	213.06a	119.35cd	9.34a	5.06ab	36.34cd	40.70ab
	V2	41.57ab	33.29abc	189.14ab	101.85d	7.00b	4.00b	34.80d	39.12abc
	V3	39.88ab	39.66a	179.04ab	169.84ab	7.12b	6.42a	40.30ab	39.83abc
	V4	38.99ab	38.61a	169.08b	140.07abcd	7.38b	5.58ab	40.77a	39.77abc
	V5	35.64b	26.05bc	169.11b	128.31bcd	7.13b	4.45ab	39.87ab	39.08bc
	V6	42.17ab	39.83a	202.09ab	181.85a	7.56ab	6.16a	39.32ab	40.94a
	V7	40.69ab	37.81a	194.62ab	181.45a	6.39b	5.89a	40.40ab	39.54abc
	V8	38.16ab	38.02a	182.93ab	183.21a	7.68ab	6.36a	40.83a	38.51c
	V9	36.05ab	35.74ab	166.88b	166.72ab	7.50ab	6.53a	39.34ab	39.02bc
	V10	37.70ab	22.96c	186.72ab	147.17abc	7.22b	4.61ab	37.83bc	38.75c
	Grand mean	39.32a	34.43b	184.94a	150.97b	7.43a	5.47b	39.02b	39.53a
	ANOVA								
	V	*	***	**	***	**	***	***	**
	E	***		***		***		**	

	Pn		C		Tr		Tleaf	
V	ww	ds	ww	ds	ww	ds	ww	ds
V×E	***		***		***		***	

		Pn		C		Tr		Tleaf	
	V	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**
	V1	47.03a	22.66c	193.03a	78.41c	7.28ab	4.00b	38.75b	42.86ab
	V2	42.37abc	29.28abc	189.03a	108.90bc	7.25ab	5.17ab	39.98a	42.72ab
	V3	41.56abc	35.05ab	191.45a	140.03ab	6.70abc	5.73ab	40.44a	41.68bc
	V4	37.76bc	34.51ab	137.08b	135.79ab	6.12c	5.40ab	38.30bc	43.11a
	V5	41.08abc	27.06abc	167.77ab	96.88bc	7.24ab	4.96ab	39.94a	40.73c
	V6	38.79abc	26.58abc	165.52ab	94.97bc	6.89abc	5.23ab	40.50a	42.12ab
	V7	43.72ab	35.59ab	194.77a	177.36a	7.65a	6.18a	37.36c	42.34ab
Year 2019	**V8**	34.15c	27.81abc	164.44ab	98.39bc	6.56bc	4.78ab	40.00a	40.62c
	V9	43.24ab	25.57bc	190.44a	93.53bc	7.14abc	4.64ab	37.63bc	43.27a
	V10	44.10ab	36.41a	197.92a	134.17ab	7.61a	6.11a	38.67b	42.06ab
	Grand mean	41.38a	29.90b	179.14a	115.88b	7.04a	5.22b	39.16b	42.15a
	ANOVA								
	V	**	***	***	***	***	*	***	***
	E	***		***		***		***	
	V×E	***		***		**		***	

		Pn		C		Tr		Tleaf	
	V	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**	**ww**	**ds**
Both years	**Y**	ns		***		**		***	
	V×Y	***		***		***		*	
	E×Y	***		***		ns		***	
	V×E×Y	***		***		**		**	

ww: well-watered; ds: drought stress; Pn: photosynthesis rate; C: stomata conductance; Tr: leaf transpiration; Tleaf: leaf temperature; SDW: Straw dry weight; V: variety; E: environment; Y: year; *** significant at p = 0.001; ** significant at p = 0.01; * significant at p = 0.05; ns: not significant. The means with the same letters are not significantly different. The bold values indicate the highest and lowest value measured.

The RLD was estimated by RID along the soil profiles using the geometrical model for both ww and ds treatments at the end of the stress. Our results showed a strong and significant effect of water deficit on the number of total roots (NTR) and RLD profiles (see Table 6).

Varieties V1 and V8 exhibited the highest NTR in ww and ds conditions respectively, while V2 and V10 exhibited the lowest in ww and ds conditions respectively. Among varieties, V4 exhibited the lowest RLD (0 cm – 120 cm) in both the ww and ds environment. Under drought stress, V1 and V8 recorded the strongest RLD in the shallow horizon (0 cm – 50 cm) and deep horizon (60 cm – 120 cm) respectively (see Table 6). From the data presented in Table 6, the global trend of the varieties' root system's responses to early drought stress is highlighted on Figure 4. Drought stress induced significant reduction of RLD in the 0 cm – 50 cm soil horizon; it increased in the 60 cm –120 cm deep soil layers.

Table 6

Average Performance of Sorghum Varieties for Root Traits Under Well-watered and Drought Stress Conditions

	NTR		**RLD [0-120cm]**		**RLD [0-50cm]**		**RLD [60-120cm]**	
V	ww	ds	ww	ds	ww	ds	ww	ds
V1	63.00a	28.66ab	1922.80a	1687.83g	3457.35c	2764.00a	800.02c	1578.33c
V2	32.00f	22.33cd	1760.68bc	2041.48c	3286.61e	2698.90b	654.07f	1571.89c
V3	40.33c	26.00bc	1751.29bc	1769.92f	3358.45d	2435.41f	648.08f	1294.57e
V4	50.33b	31.66a	1467.24e	1574.29h	2519.95h	2236.74g	715.29e	1090.53f
V5	62.66a	28.66ab	1781.89bc	1945.37e	3245.57e	2641.44c	719.73e	1448.18d
V6	40.00cd	28.66ab	1739.46bc	1993.00d	3564.50b	2520.00e	873.33a	1421.00d
V7	36.00e	25.33bc	1827.72b	2190.90b	3311.3de	2598.55d	772.75cd	1807.34b
V8	42.00c	30.66a	1991.88a	2453.95a	3659.27a	2704.23b	800.89c	2266.67a
V9	37.00de	25.00bcd	1625.93d	1687.83g	2738.30g	2271.24g	831.38b	1271.11e
V10	37.00de	21.33d	1696.45cd	1757.95f	3121.66f	2428.02f	763.37d	1279.32e
Grand mean	44.03a	26.83b	1758.61b	1897.27a	3214.64a	2522.88b	757.89b	1502.8a
ANOVA								
V	***	***	***	***	***	***	***	***
E	***		***		***		***	
V×E	***		***		***		***	

ww: well-watered; ds: drought stress; NTR: number of total roots; RLD: root length density (m m^{-2}); [0–120 cm], [0–50 cm] and [60–120 cm] represent the depth considered; V: variety; E: environment; *** significant at p = 0.001. Means with the same letters are not significantly different. The bold values indicate the highest and lowest value measured.

Figure 4

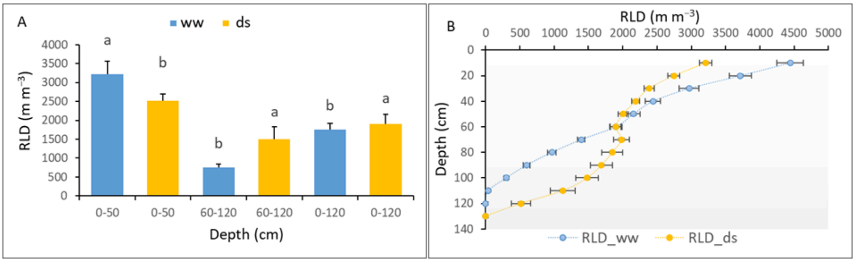

Figure 4 – Root Length Density (RLD) of Sorghum Varieties Under Well-watered (ww) and Drought Stress (ds) Conditions at the End of the Stress Period

Notes. (A) RLD distribution at [0-50], [60-120] and [0-120] depth horizons (B) Impact of water deficit on RLD profile. Data are means +/- standard error. Significant differences are indicated by different letters.

4. Relationship Between Vegetation Indices and Sorghum's Growth Traits

Results presented in Table 7 show the relationship between LAI, biomass, and vegetation indices. Nonlinear and linear regression models were fitted using the 2018 field data set (n = 390, calibration data). Regression analysis revealed a good relationship between LAI or biomass with NDVI, CTVI, GNDVI, MSAVI2, and SR. To assess the performance of vegetation indices to estimate LAI, we compared the coefficients of determination (r^2) of the relationships between NDVI, CTVI, MSAVI2, SR, and LAI that were respectively of 0.83, 0.82, 0.76 and 0.77 with highly significant p values. However, the r^2 for biomass estimation using the same indices were comparatively lower than those for LAI (0.6, 0.6, 0.57, and 0.47).

Table 7
Regression of Sorghum LAI and Biomass on Vegetation Indices (n = 390)

Vegetation indices	Regression models	r	r^2	P-value
NDVI	$LAI=0.3732*e^{2.9648*NDVI}$	0.91	0.83	<0.001
CTVI	$LAI=0.0069*e^{5.5322*CTVI}$	0.9	0.82	<0.001
MSAVI2	$LAI=0.3392*e^{2.7498*MSAVI2}$	0.9	0.82	<0.001
SR	LAI=0.4438*SR+0.0126	0.87	0.77	<0.001
NDVI	$Biomass = 3.1153*e^{3.7021*NDVI}$	0.77	0.6	<0.001
CTVI	$Biomass = 0.0206*e^{6.9446*CTVI}$	0.77	0.6	<0.001
MSAVI2	$Biomass = 2.7357*e^{3.4587*GNDVI}$	0.77	0.6	<0.001
SR	Biomass = 6.0128*SR + 0.8947	0.68	0.47	<0.001

NDVI, CTVI, MSAVI2 and SR: vegetation indices; r: coefficient of correlation; r^2: coefficient determination; LAI: leaf area index.

Figure 5 shows the NDVI plots with the corresponding LAI. The LAI values varied from 0.3 $m^2\ m^{-2}$ to 5.7 $m^2\ m^{-2}$ per plant across varieties, treatments, and developmental stages during the calibration trial in 2018. A saturation of the different vegetation indices was observed above LAI values higher than 4 $m^2\ m^{-2}$ per plant. To test the variance of calibration models, an ordinary least squares linear regression between calculated and measured LAI was done, and it revealed an r^2 value of 0.8 for LAI (see Figure 5). The ANOVA revealed highly significant effect of varieties, environment, and the interaction (V*E) ($p<0.05$) on both calculated and measured LAI and biomass with almost the same values (see Tables 8 and 9).

Figure 5

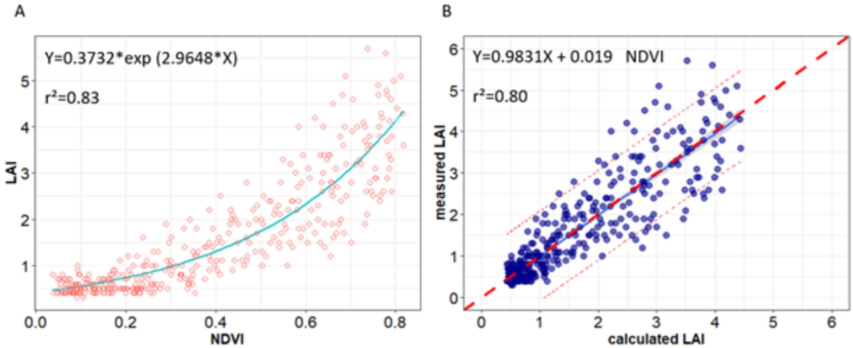

Figure 5 – Calibration of LAI prediction model from NDVI vegetation index

Notes. (A) Relationship between normalized difference vegetation index (NDVI) and leaf area index (LAI); (B) Measured LAI vs. corresponding LAI values predicted using empirical equation in Figure 5A. The dashed red line in the graph is the 1:1 line.

Table 8
ANOVA of Leaf Area Index Measured (LAIm) and Calculated from Vegetation Indices (LAIc) and Average Performance of the Varieties Under Well-watered and Drought Stress

	LAIc_NDVI		**LAIc_CTVI**		**LAIm**	
V	ww	ds	ww	ds	ww	ds
V1	1.5	0.62	1.53	0.62	1.9	0.6
V2	1.56	0.61	1.59	0.61	1.9	0.8
V3	2.09	0.7	2.12	0.72	1.57	0.9
V4	1.6	0.58	1.63	0.57	1.4	0.45
V5	1.95	0.56	1.97	0.56	2.23	0.6
V6	1.39	0.7	1.43	0.7	1.63	0.57
V7	2.01	0.53	2.03	0.52	1.9	0.47
V8	1.93	0.68	1.96	0.69	2.63	0.8
V9	1.78	0.64	1.81	0.65	1.53	0.67
V10	1.74	0.48	1.77	0.47	1.57	0.53
Mean	1.75	0.61	1.78	0.61	1.83	0.64
V	*		*		**	
E	***		***		***	

	LAIc_NDVI	LAIc_CTVI	LAIm
V*E	*	*	*

V: varieties; E: environment; ww: well-watered; ds: drought stress; CTVI and NDVI: vegetation indices; Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

Table 9
ANOVA of the Biomass Per Plant Measured (BPPm) and Calculated from Vegetation Indices (BPPc) and Average Performance of the Varieties Under Well-watered and Drought Stress

	BPPc_MSAVI2		BPPc_SR		BPPm	
V	ww	ds	ww	ds	ww	ds
V1	17.62	5.53	21.12	9.69	18.3	15.7
V2	18.27	5.38	22.08	9.54	22.55	10.79
V3	25.85	6.65	27.56	10.5	19.11	12.36
V4	18.73	4.96	22.38	9.01	17.38	7.9
V5	23.94	4.73	26.1	8.93	29.82	11.84
V6	15.77	6.62	20.49	10.49	23.87	11.39
V7	24.47	4.35	28.25	8.57	35.72	8
V8	23.59	6.32	26.84	10.36	27.32	9.21
V9	21.52	5.76	24.51	9.87	22.49	18.88
V10	21	3.75	24.55	7.91	18.28	5.86
Mean	21.08	5.42	24.39	9.5	23.48	11.31
V	*		*		***	
E	***		***		***	
V*E	*		**		***	

V: varieties; E: environment; ww: well-watered; ds: drought stress; MSAVI2 and SR: vegetation indices; Significance codes: '***' 0.001 '**' 0.01 '*' 0.05

5. Assessment of the Impact of Water Treatment on UAV Derived Traits

The combined analysis of variance revealed highly significant effect ($P \leq 0.05$) of the environment (E), variety (V), and their interaction (V*E) on all the vegetation indices under study (see Table 10). In ww conditions, the varieties recorded on average 0.6, 1.08, 0.76, 7.37 for NDVI, CTVI, MSAVI2, and SR respectively; the stressed plants showed lower values (i.e., 0.37, 0.90, 0.44, and 3.01). In ds conditions, the variety V3 exhibited the highest indices (0.59, 0.94, 0.66 and 4.02 for NDVI, CTVI, MSAVI2, and SR); V10 had the lowest (0.20, 0.83, 0.25, and 1.74).

Table 10
Average Performance and ANOVA of the Vegetation Indices of the Varieties Under Well- watered and Drought Stress

	NDVI		**CTVI**		**MSAVI2**		**SR**	
V	ww	ds	ww	ds	ww	ds	ww	ds
V1	0.63	0.38	1.06	0.92	0.71	0.46	6.83	3
V2	0.68	0.37	1.08	0.91	0.76	0.44	6.77	3
V3	0.73	0.59	1.11	0.94	0.81	0.66	7.97	4.02
V4	0.7	0.33	1.09	0.89	0.77	0.4	7.53	2.71
V5	0.71	0.39	1.1	0.94	0.79	0.47	7.91	2.85
V6	0.62	0.36	1.05	0.89	0.7	0.42	5.69	3.24
V7	0.74	0.28	1.11	0.88	0.81	0.35	8.59	2.2
V8	0.74	0.45	1.11	0.94	0.81	0.53	8.17	4.46
V9	0.7	0.4	1.09	0.94	0.78	0.49	6.99	2.92
V10	0.67	0.2	1.08	0.83	0.75	0.25	7.33	1.74
Mean	0.69	0.37	1.08	0.9	0.76	0.44	7.37	3.01
V	**		**		***		*	
E	***		***		***		***	
V*E	*		*		*		*	

V: varieties; E: environment; NDVI, CTVI, MSAVI2 and SR: vegetation indices (VIs); ww: well-watered; ds: drought stress; Significant codes: '***' 0.001 '**' 0.01 '*' 0.05

Results presented in Figure 6 showed the general trend of the evolution of VIs during plants growth in both ww and ds conditions. The vegetation indices of nonstressed plants gradually increased to reach their maximum at the 60th DAS (flowering time) before dropping slightly. In the stressed plots, the vegetation indices initially recorded a slight increase but then water deficit induced a reduction that was followed by a progressive increase after rewatering.

However, the VIs values of stressed plants did not recover values of the nonstressed plants. The results highlighted in this study testify the relevance of VIs to capture the differences induced by drought and that occurred from the 30th DAS to the 55th DAS. The post flowering decrease of the VIs observed in the ww treatment was due to the saturation of the VIs as plants have grown up enough in this environment.

Figure 6

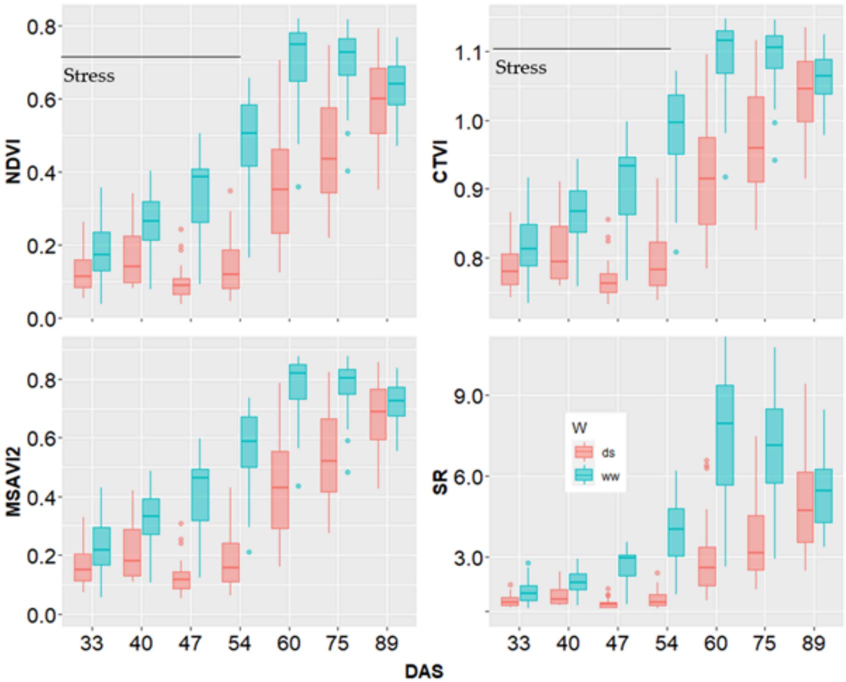

Figure 6 – Dynamics of Estimated Vegetation Indices Under Well-watered and Drought Stress Conditions

Note. Box plots represent the estimations for all the 10 sorghum varieties at a given stage. NDVI, CTVI, MSAVI2 and SR: vegetation indices; DAS: days after sowing; ds: drought stress; ww: well-watered.

Discussion

1. The Adaptive Behavior of the Sorghum Varieties Studied

The stress characterization revealed very negative values of water potential (WP = -5 bars) at the end of the stress period. This can be explained by the intensity of the stress experienced by the plants (FTSW = 0.3). To counteract the water deficit that occurs in their tissues, plants implement water retention mechanisms with very high energy. Consequently, it is necessary to provide equivalent energy to extract this water from the tissues (Brou et al., 2007). The behavior of the sorghum varieties, which consists in maintaining a high level of hydration despite the stress pressure, reflects a dehydration tolerance mechanism, with a low water potential of the tissues (Levitt, 1985). This limits cell growth because of loss of turgidity.

Water-limiting conditions lead to altered cell elongation, mainly due to low water flow from the xylem to neighboring cells (Fahad et al., 2017; Nonami, 1998). The number of leaves and the size of each leaf were reduced in drought conditions because their expansion depends on the turgor pressure and the amount of water assimilated. This induced a decrease in plant biomass accompanied by a reduction in leaf appearance and plant growth. Regarding physiological traits, drought stress causes a decrease in the transpiration rate, photosynthetic activity, and stomata conductance (Dwivedi et al., 2008; Fracasso et al., 2016). This adaptation mechanism also was revealed in pearl millet (Kholova et al., 2009, 2010) and cowpea (Belko et al., 2012). Under water deficit, the diffusion of CO_2 to the carboxylation sites is limited because of stomata closure and increased mesophyll resistance. This inhibits the transport of electrons, leading to an imbalance between the electron transport rate and

CO_2 fixation rate (Verma et al., 2018). The photosynthetic performance is one of the parameters providing useful and quantitative information on plants condition and vitality (Banks, 2018; Oukarroum et al., 2007; Zegada-Lizarazu & Monti, 2013). Tingting et al. (2010) showed that the process of photosynthesis is sensitive to changing environmental conditions, and the way in which plants adapt to their environment is propitious to photosynthesis. The recovery of photosynthesis upon rewatering indicates that the PSII systems had recovered their ability to deal with the absorbed light and the accumulated energy. Hence, oxidative permanent damage may not have occurred at the early growth stages, or as suggested by Oukarroum et al. (2007), the maximum quantum yield of photochemistry was not affected by the drought. The drop of plant growth rate caused by the lack of water during a given period often leads to difficulties in covering the normal development in terms of height or biomass (Hud et al., 2016). This behavior is not always a disastrous consequence. It could be a means of adaptation that allows the plant to maintain its development but at a slower pace. This was the case of the variety V6, for instance, which produced well despite a low DRI in height and biomass. These are part of physiological functioning that confer drought tolerance to sorghum (Hadebe et al., 2017; Harris et al., 2007; Kapanigowda et al., 2013). The agro-physiological behavior of a plant depends on the genotype, the severity of the drought, and the time of occurrence (Chaves et al., 2002; Jaleel et al., 2008). Early water stress acts differently on sorghum varieties depending on the variety's stage of development. It is well-known that when drought occurs at the vegetative stage before panicle exertion, plants recover better. This may explain why the agronomic performances of some long-duration varieties of the *guinea* and *bicolor* breed (V1, V4) were weakly affected by early cycle drought. Long-duration varieties were able to catch up and stabilize production despite a lack of water at the early stage. According to Araus et al. (1989), this phenomenon is due to stomata control, which is more effective in the young growth stages. This could have been the case of variety V1, which responded to water deficit by closing its stomata, thus allowing it to limit exchanges with the environment until water conditions become favorable and the growth could resume and compensate for the losses due to drought. Contrariwise, V4 showed the lowest DRI and a slight variation of stomata conductance and yield under drought stress. A hypothesis is that this variety recovered well after the 2 weeks allowed for recovery measurement. However, the drought adaptation conferred by the long cycle is not sufficient to consider such varieties appropriate for the future. Previous studies have shown that the duration of drought episodes at the beginning of the season is likely to increase with the worsening of global climate change impacts (Blanc, 2012; Vadez et al., 2012), therefore even long-duration varieties may be affected by early drought stress if the duration is long.

Roots play an important role as a support, but also provide the plant with the water and mineral elements it needs. Thus, their study represents a very effective means of characterizing drought adaptation. Some authors showed that the spatial distribution of root length density determines water and nutrient uptake (Intergovernmental Panel on Climate Change, 2014). In the present study, the varieties V1 and V8 turned out to be very interesting. They yielded well under drought, and their adaptations were mainly based on a high RLD (60 cm – 120 cm) (V8) and the increase of dead leaves (V8 and V1) contrarily to V4, which had the lowest RLD (60 cm – 120 cm) and a low grain yield. Additionally, some varieties have densified their root system to be able to exploit a larger surface area of soil and to increase the absorption of water and mineral nutrients (Comas et al., 2013). The high root density at depth allows them to reach moisture in the deeper soil layers and compensate for the lack of water supply.

Although the varieties V3, V4, and V5 were less productive, they could be of high interest for height or fodder breeding programs. Varieties V1, V2, V8, and V9 could be devoted for grain yield breeding. Phenotypic evaluation of germplasm can be useful for characterization, conservation, and maintenance of genetic resources (Naoura et al., 2019). This study revealed a large agro-morphological diversity of quantitative traits. Overall, the results showed that plant response to early drought was genotype dependent (Sinclair et al., 2018) and some varieties expressed a strong ability to reduce water loss by decreasing leaf transpiration rate through stomata closure and increasing the number of dead leaves. These were among the adaptation strategies used by the studied varieties to tolerate drought stress conditions in both seasons.

2. Monitoring Plant Growth by UAV Based Phenotyping

Recent advances in high throughput field phenotyping have boosted the power of physiological breeding (Araus & Cairns, 2014; Fahlgren et al., 2015; Hu et al., 2018; Reynolds & Langridge, 2016). Currently, UAV technology is an alternative to the manual collection of crop data, offering information on traits and factors affecting crop development and productivity with relatively shorter time and lower cost (Du & Noguchi, 2017; Yu et al., 2016). The moderate to strong relationships (see Table 7) found between the UAV-derived plant spectral traits and the leaf area index and the biomass indicate that UAVs could be useful for phenotyping West Africa sorghum genotypes (Gano et al., 2021). The NDVI is an indicator of the combined effects of chlorophyll concentration, canopy leaf area, and yield (Erdle et al., 2011). The estimation of the NDVI can be used as a reference index for the dynamic monitoring of the biomass changes during the growth season of sorghum. NDVI estimates are influenced by many factors, such as measurement time, sensors, and environmental conditions (Crusiol et al., 2017), and there is no one absolutely accurate measurement method for NDVI estimation.

Improved precision would also contribute to further applications for field management (Foster et al., 2017). Results presented herein demonstrate the importance of using NDVI related vegetation index as indirect selection criteria by reporting genetic variation for VIs among varieties, the effect of water treatment on VIs and their interaction with varieties, and the relationships between VIs and LAI and biomass of sorghum. This attests the ability of VIs in estimating growth rate, biomass accumulation during the vegetative stage and yield set up (Babar et al., 2006).

3. Key Traits Involved in Drought Tolerance for Breeding

As a major challenge for agricultural production, drought tolerance is a prime target for molecular approaches to crop improvement. To obtain significant results, these approaches must be based on phenotyping protocols that are appropriate at all stages of plant development (Salekdeh et al., 2009). Because drought adaptation traits are complex and polygenic, the understanding of their physiological and genetic basis is still incomplete. This challenge comes at a time when plant biologists are witnessing an explosion in the availability of new high-throughput technologies and genomic information. However, the identification of preferred selection criteria remains unclear and still makes phenotyping laborious. According to Passioura (1977), the conceptual framework for drought phenotyping is based on the equation expressing the product yield of WU (quantity of water used), WUE (conversion of WU into dry biomass), and HI (the fraction of dry matter converted into grain). Therefore, it is important to design experiments to test these factors by distinguishing the impact of WU and WUE on production. In other words, when looking at productivity, it is important to identify the effects of growth stress that may affect assimilations transport. By considering these components of performance individually, it is possible to target traits more effectively in relation to environmental constraints. In the case of early-cycle water stress, there are several key phenotypic traits highlighted (see Table 11) to help target phenotyping. In addition, it would be useful to select high yielding genotypes that are stable across environmental conditions and years. To do so, it would be interesting to follow growth-related traits such as plant height and NLA, DWP, Tr and Pn because these traits are susceptible to environmental changes.

Table 11
Example of Traits Associated with Different Yield Factors Worth to Phenotype Under Conditions of Early-cycle Water Stress in Sorghum

Traits	Stage	Phenotyping technique	Interest for breeding
Root Length Density (RLD)	Growth	Count	Yield
Number of adventitious roots	Growth	Count	Yield
Soil water stock	Growth	Metric	Yield
Biomass rate	Growth	Metric	Biomass
Plant height rate	Growth	Metric	Biomass
Dead leaves weight	Growth	Metric	Yield
Photosynthesis rate	Growth	Metric	Yield
Transpiration rate	Growth	Metric	Yield
NDVI	Growth	Metric	Biomass
Grain weight	Harvest	Metric	Yield
Number of grains	Harvest	Count	Yield
Stem dry weight	Harvest	Metric	Biomass

Moreover, this study demonstrated successful and rapid assessment of NDVI related VIs (CTVI, MSAVI2 and SR) using a UAV platform that showed high accuracy in assessing variation in plant development. The accuracy of the UAV platform was validated by ground truth data, and it proved a significant advantage of UAV over the handheld data acquisition platform from the stem elongation stage to late grain filling stage, especially under water- limited conditions.

Drought-prone environments are diverse and the biotic and abiotic stresses that affect yield during drought periods are numerous (Richards et al., 2002). Therefore, our objective is not to propose unique criteria for drought stress phenotyping. Rather, we suggest that each experiment be conducted with a specific, realistic goal and with WUE and yield set up as reference traits (Venuprasad et al., 2007). Such reference traits will ensure the relevance of field results that are assessed and deposited in public databases for a standardized recording and reporting of drought-related phenotypic data.

Conclusion

This study is justified by the challenge that researchers have set to improve adaptation to early drought stress in cereals, particularly sorghum. We have shown the impact of water deficit on sorghum growth and development. The early stress is a major factor in the evolution of biomass, height, and leaf development. Even though it occurred early, its impact leads to yield instability. This study also highlighted plant adaptation mechanisms under early water deficit based on growth; photosynthesis and transpiration reduction; senescence increase; stomata closure; and roots length density increase. We also highlighted the ability of UAV platform to phenotype drought stress in West Africa sorghum varieties. Finally, we proposed key phenotyping traits that involve the different factors that govern production for a more efficient characterization of drought adaptation. Future areas of study could include phenotyping entire sorghum collections in different growing conditions during the year to better fix the adaptation mechanisms. Based on the predictions of precariousness linked to climate change, it would be more than necessary to select varieties that are able to adapt and stabilize performance independently of the season and year.

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