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Performance of Three Sorghum Cultivars under Excessive Rainfall and Waterlogged Conditions in the Sudano-Sahelian Zone of West Africa: A Case Study at the Climate-Smart Village of Cinzana in Mali

Manuel Müller [1],* , **Siaka Dembélé [2]** , **Robert B. Zougmoré [3]** , **Thomas Gaiser [1]** and **Samuel T. Partey [3]**

[1] University of Bonn, DE-Katzenburgweg 5, 53115 Bonn, Germany; tgaiser@uni-bonn.de
[2] Institut d'Economie Rurale (IER), Ségou BP 214, Mali; siaka.bioscience@gmail.com
[3] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Bamako BP 320, Mali; r.zougmore@cgiar.org (R.B.Z.); s.partey@cgiar.org (S.T.P.)
* Correspondence: manuel.mueller@gmx-topmail.de

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Abstract: Recent climate analyses show trends for increasing precipitation variability with increasing precipitation sums in Mali. The increasing occurrence of temporary intra-seasonal droughts and waterlogging longer than a week demands climate-smart solutions. Research has focused on water deficits since the 1980s. However, besides droughts, waterlogging can restrict productivity of sensitive cash and staple crops as cotton and corn. The year 2019 offered the historically unique opportunity to monitor waterlogging effects with 1088 mm precipitation in the rural commune Cinzanawith an isohyet of 681 mm. Impacts of two extreme downpours on three sorghum cultivars were monitored in a farmers-field experiment with three replications. All sorghum cultivars performed well in 2019 with significantly higher grain and above ground biomass yields than in the reference year 2007, with well distributed rainfall in Cinzana. "Jakumbè" (CSM63E) produced significantly higher grain yields than the hybrid cultivar "PR3009B" bred for high harvest index. The local cultivar "Gnofing" selected by local farmers produced significantly higher above ground biomass. All cultivars tolerated without severe stress symptoms 20 days waterlogging and 72 h inundation. Further waterlogging resilience research of other crops and other sorghum cultivars is needed to strengthen food security in Mali with expected increasing precipitation variation in the future.

Keywords: inundation; waterlogging; climate change adaptation; flooding; millet; Sahel

1. Introduction

Stronger rainfall variability is predicted for the end of the 21st century according to most of the CMIP5 scenarios presented in the IPCC report of 2014 [1,2] in the Sudan–Sahelian zone of Mali [3]. Triggered by severe droughts in the 1980s, research has focused on drought mitigation strategies. Investigating the state of research concerning water logging effect as forecast and adoption, lacking data have been identified for multiple crops [4,5]. Increasing average precipitation with a strong modulation of rainfall amounts [5,6] demand for providing field data representing the expected higher probability of rainy seasons with excessive rainfalls. In 2019, 1.729 households were affected by floods following extreme downpours [7].

Especially the currently most important staple crop, corn, and the cash crop, cotton, are susceptible to water logging [8,9].

Since 1980, the occurrence of extreme precipitation events has increased significantly in West Africa which leads to increasing occurrences of inundation [9].

Since 2000, Mali's population has doubled with 19 million inhabitants in 2018 [10,11]. In Ségou region, annual food insecurity occurs before harvest from June to August with 87% of the population affected in June 2018 [12]. The 18.2% of the children aged 6–28 months are malnourished and 26.6% have stunned growth [10]. From the total population of Ségou, 9.8% are malnourished, and rural regions are affected stronger (18.2%) than urban regions (6.7%) by food insecurity.

The Sudan-Sahelian agricultural production zone of Ségou is dominated by millet, sorghum, cowpea, sesame, fonio, and peanut production with herding of cows, sheep, and goats. Millet (1.9 million tons (2017) is a very resilient cereal with little demand in fertilizer and water [13,14]. Many cultivars are susceptible to waterlogging [15], which has negative implications for food security in the context of more excessive rainfalls during a wetter core rainy season [3]. Corn production is increasing rapidly from 2.3 to 3.6 million tons in 2017 [14] fueled by fertilizer subsidies [16]. Early maturing corn cultivars can be harvested in September [17] but is susceptible to waterlogging [8,18] after erratic rainfalls. However, sorghum (1.3 million tons 2017 [14]) is a robust crop both in wet years as well as in dry years with erratic rainfalls due to lower crop water demand than corn and due to waterlogging tolerance [15,17]. However, it seems that sorghum has major differences in cultivar sensitivity to waterlogging. Optimum yields in sorghum ranges from 2.5 to 5 t ha^{-1} under full irrigation, which are higher than pearl millet (1.5–3.5 t ha^{-1} for improved varieties), but lower than corn (3–8 t ha^{-1}), although the latter demands 100 kg ha^{-1} more urea fertilizer [17,19,20].

Daily average evapotranspiration is 4.1 mm day^{-1} at Ségou [21] during the growing season. At the Climate-Smart Village of Cinzana, several climate-smart agricultural water-saving measures have been tested. However, rainy season with excessive rains have also been occurring more frequently since the 1990s (Figure 1). With average precipitation of 681 mm (1950–2019) in Cinzana, sorghum cultivars of isohyets that require 500 to 700 mm water supply are well adapted, even though the average precipitation from 2000 to 2019 in Cinzana has showed an increasing trend.
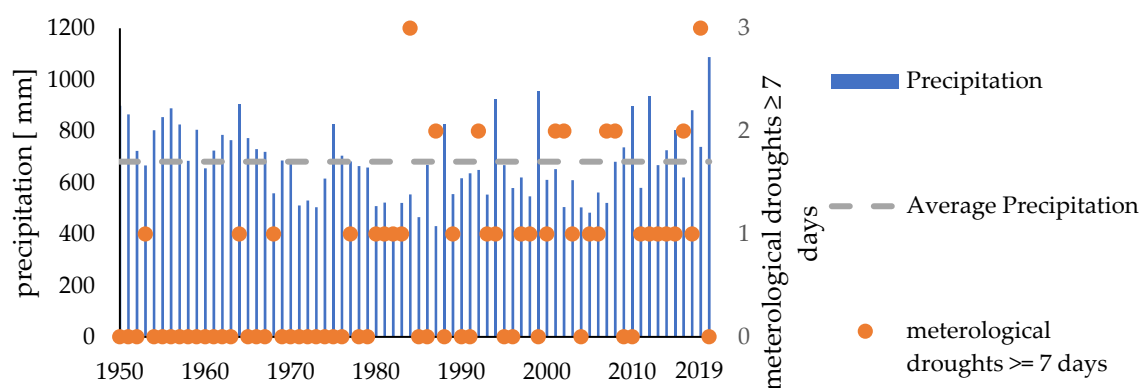
Figure 1. Annual Historic Precipitation at Ségou from 1950 to 2019. Quantity of short droughts ≥ 7 days (orange dots) on the right scale. Data Provided by Vaksmann, IER [22].

In this paper, flooding or inundation stands for visible surface coverage, waterlogging stands for saturated soil where water does not necessarily need to be visible at the surface [23]. Long term saturation of the rooting zone leads to negative effects on crops defined as waterlogging effects. Roots are affected by anaerobic conditions in the root zone [7,20]. Waterlogging causes oxygen deficiency and increased concentrations of gases like carbon dioxide and ethylene which affect the root development negatively. Nitrogen uptake is reduced because aerobic bacterias' activities are reduced and Fe^{2+} toxicity and Mn^+ toxicity can occur [23].

However, most of the knowledge about waterlogging tolerance of sorghum is derived from pot experiments and little is known about the susceptibility of local and improved sorghum cultivar. Therefore, in an on-farm field experiment, the following hypotheses were tested under field conditions,

taking advantage of the unique opportunity of naturally occurring 20 days of waterlogging from 8 leaves to flag leaf stage: (1) sorghum cultivars respond differently to waterlogging with respect to grain production, (2) sorghum cultivars respond differently to waterlogging with respect to above ground biomass production (3), all cultivars respond positively to late irrigation during grain filling with increased biomass production and yield.

The research aim is to prove if morphological stress symptoms caused by water are occurring and to evaluate their severeness based on the yield effects on grain and above-ground biomass (AGB).

2. Materials and Methods

2.1. Experimental Design

The current study was set up as a two factorial participatory field experiment to evaluate different sorghum cultivars (factor 1) under two different late precipitation scenarios (with and without late irrigation, factor 2).

2.2. Site Conditions

The research was implemented in 2019 at N'Gakoro, which belongs to the Climate-Smart villages (CSV) of Cinzana (Figure 2). The CSVs are part of the Agricultural Research for Development (AR4D) sites in West Africa [24]. One of the flagships of the research Program on Climate Change, Agriculture and Food Security (CCAFS) is developing and testing climate-smart agricultural (CSA) practices in participatory field research.
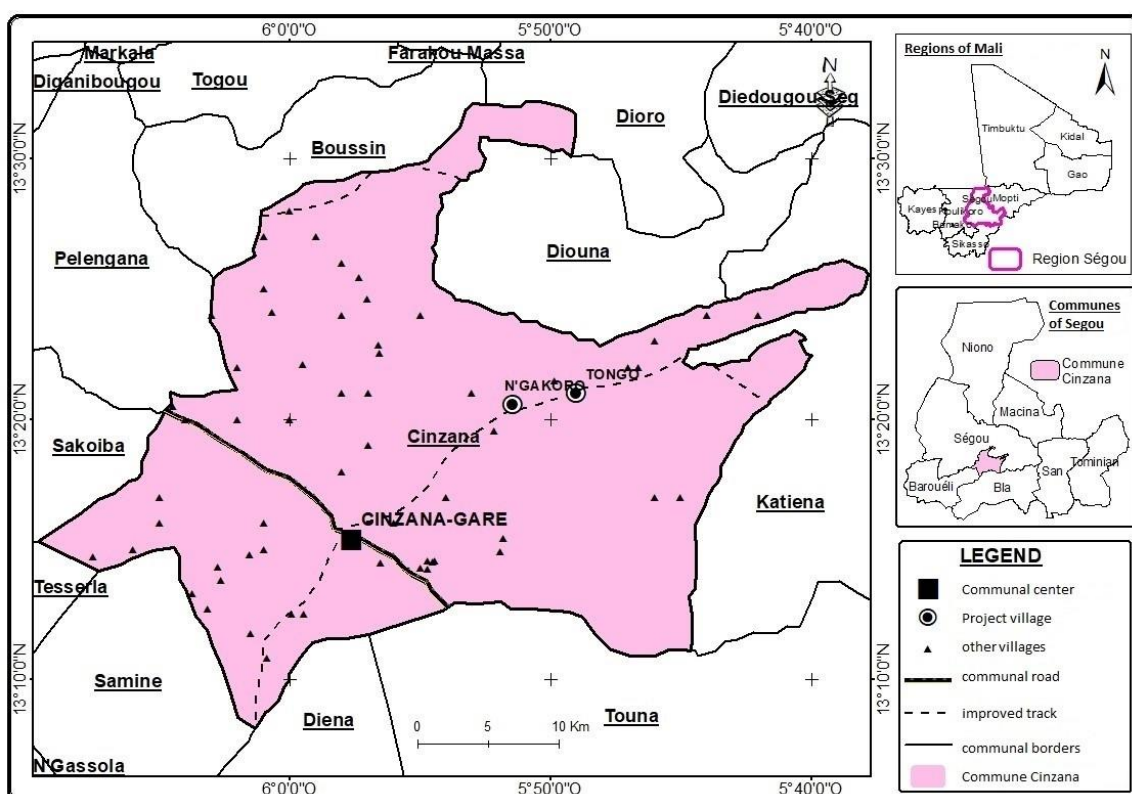
Figure 2. Climate-Smart village of Cinzana in Ségou Region in Mali, West Africa 13°20′ N 5°51′ W. Research villages N'Gakoro and Tongo [24].

N'Gakoro is located at 13°20′ N 5°51′ W. The main rainy season is from May to September and the cropping season usually lasts from June to October. Long-term minimum and maximum monthly air temperatures are 21 °C and 41 °C, respectively.

The field experiment was implemented on a lowland plain with <1.5° slope on a Calciferric Vertisol of parental river material with very low soil nutrient contents (Table 1). Millet was cultivated in the previous season and sorghum–cowpea and corn–sorghum intercropping as well as millet have been cultivated during the last 20 years. Decomposed surface residues were < 100 kg ha^{-1} and below a shallow plow horizon of 10 cm with 2.3 % soil organic matter content. Root abundance as well as biological activity decreased strongly below 30 cm.

Table 1. Textural and chemical soil properties (Calciferric Vertisol) at N'Gakoro (13°20′35.9″ N 5°51′24.8″ W). Analyzed with auto capture pH-meter, CN-Analyzer, Optical Plate reader for P and Photometer for K (all K values were too low for measurements). ∅ = too low for measurement. pH measured in H$_2$O solution, C and N analyzed by Hecker-standard, P and K measured by CAL-method.

Depths (cm)	Clay (%)	Silt (%)	Sand (%)	Bulk Density (g cm^{-3})	pH	C (g kg^{-1})	N (g kg^{-1})	P (mg kg^{-1})
0–20	45.2	16.7	36	1.23	6.53	0.52	0.04	∅
20–40	54.20	15.70	29.20	1.36	6.19	0.34	0.03	∅
40–60	47.5	15.1	29.1	1.28	7.14	0.28	0.02	0.76
60–80	46.6	18.2	34.1	1.07	7.61	0.33	0.03	0.36
80–100	46.2	18	35.1	1.31	7.75	0.26	0.02	3.89
100–120	46.4	19.3	33.2	1.54	7.91	0.19	0.02	∅
180–200	42.2	20.1	35.5	1.36	8.14	0.20	0.02	0.41

2.3. Experimental Material

A local dual-purpose cultivar "Gnofing" was tested against an improved dual-purpose cultivar "CSM63E" and the hybrid "PR3009B" bred for reduced stover and higher harvest index. "Gnofing" was selected as the local cultivar based on the farmers preference "CSM63E" is a regional landrace (local name: "Jakumbè") for regions at isohyets between 400 and 700 mm. It has been bred for lower photoperiod sensitivity and for higher tolerance to drought and waterlogging [17]. "PR3009B" is a hybrid bred for higher harvest index and it should be more drought sensitive due to reduced stay green traits [25].

2.4. Moisture Treatment

In many years, water deficiency during grain filling of sorghum is reducing grain yields. Within the last ten years, precipitation events during grain filling of sorghum surpassing daily evapotranspiration occurred usually by the end of October. On average, one additional precipitation event occurred within the month of October. Therefore, besides the control (no irrigation), irrigation water volumes of 20 mm were applied during grain filling on 10 and 30 October 2019.

2.5. Soil Analysis

Soil samples from two soil profiles at the edges of the experimental field were taken from soil layers with a thickness of 20 cm (Table 1). Furthermore, soil samples from 0–30 cm and 30–60 cm were taken in each plot with an Edelman soil auger from each plot. In each case, loose samples of 300–500g for nutrient analysis, and 100 cm^3 soil volumetric cylinder samples to determine bulk density were taken and then the samples were dried at 105 °C for 48 h in a drying cabinet. For determination of gravel, the samples were rolled and sieved to 2 mm. 50 g of the sieved material was taken for texture analysis. For pH measurement, 5 g of the sieved sample was dissolved in 100 mL distilled water. A CAL-solution consisting of 385 g C$_6$H$_{10}$CaO$_6$, 197.5 g C$_4$H$_6$CaO$_4$, and 447.5 mL CH$_3$COOH was prepared with 3 L of distilled water and diluted fivefold. Afterwards, double samples of 5 g were dissolved in 100 mL CAL and shaken for 2 h before filtering for P and K analysis of the solution. For Phosphorus (P) measurement, a color reagent of 70.5 mL H$_2$SO$_4$, 6 g of (NH$_4$)6Mo$_7$O$_{24}$•4H$_2$O was dissolved in 125 mL distilled water and 0.14 g of K$_2$(SbO$_2$)C$_8$H$_4$O$_{10}$•3H$_2$O dissolved in 125 mL distilled water was prepared. A quantity of 100 mL of the stock was mixed with 0.53 g C$_6$H$_8$O$_6$. Standard-Curves were created with 0, 10, 20, 30, 40, and 50 µL of 1 µg µL^{-1} Monopotassium phosphate

KH_2PO_4 and filled up with distilled water to 210 μL on microplates. Afterwards, 210 μL of sample filtrates and VDLUFA FG II 98. RV calibration soil filtrates (12.4 g P1 with 14.9 g K1 and 5.1 g P1 with 11.4 g K1) according to DIN38402 A45 from the laboratory for agricultural and environmental analysis (LUFA) were pipetted into the remaining slots (highest possible concentration). Every variation was pipetted for two separate filtrate samples in three repetitions. After 15 min incubation time with 40 μL of color reagent, analysis in a Biotec Power Wave XS 2 microplate reader with Gen5 software (Biotec Instruments, Inc., Winooski, VT, USA) and the settings for Phosphorus Analysis were applied. K of the filtrate solutions was analyzed with an Eppendorf F-AES ELEX 6361 flame spectrometer provided by INRES (Institute of Crop Sciences and Resource Conservation of the University of Bonn). For C and N analysis, 5 g of the soil samples were grinded with a pebble mill and double samples of 25 mg coated with tin (Sn) analyzed in a Euro EA CHNS-O Element- analyzer with Calidus 5.1 software(HEKAtech GmbH, Wegberg, Germany). They were recalculated and critical measurements were repeated.

Before sowing, germination tests were applied, and the seeds were treated with the fungicide Apron Star [26]. The experimental design resulted in 18 plots and was implemented in a randomized complete block design using ridges [27] by single blade plow with 60 cm row spacing pulled by oxen. Sowing was conducted on 13 July 2019. Each plot included 10 rows of 12 seed holes with 5–10 seeds and 2 g NPK 17-17-17 micro-dosing with 40 cm seed hole distance. Using optimum fertilizer recommendations for Cinzana region, 100 kg ha^{-1} NPK (17-17-17) were broadcasted at sowing and 50 kg ha^{-1} Urea applied after 6 weeks. On 6 August 2019, the plants were thinned to 2 plants per seed hole. Irrigation volumes of 20 mm were equally distributed into the contour line furrows during grain filling (10 and 30 October 2019).

2.6. Field Observations

Daily weather data including minimum temperature, maximum temperature, and minimum and maximum air humidity and precipitation were recorded manually during the growing season. Precipitation was read from a rain gauge and the other parameters were measured by an electric sensor device under a wooden shelter [28]. Initial and final soil moisture was recorded at 4 levels down to 1 m soil depth (0–6 cm, 30–36 cm, 60–66 cm, 100–106 cm) in two soil profiles with a Theta ML 3 Probe (Delta-T Devices Ltd., Cambridge, United Kingdom). Soil moisture in individual plots was measured in 2 weeks intervals in 0–6 cm and 30–36 cm depths. After excessive rainfalls, soil moisture was measured at 1 m to monitor the soil saturation in deeper layers [29]. Additionally, three single measurements up to 60–66 cm depths were applied during October for one plot per treatment. Additionally, visual inundation assessment was applied in 3 days intervals. Inundation is defined as standing surface water, waterlogging as a saturated soil surface with partly surface water in furrows, and moist surface differing from brighter dry surface.

Growth monitoring and stress assessment were applied in 2 week intervals assessing plant height, leaf erectness, leaf rolling, yellow and senescent leaves, as well as plant mortality. Neither severe drought stress nor severe waterlogging stress were observed, and foliar diseases and insect pest pressure were negligible.

Beginning at flag leaf stage, phenological development (Flag leaf, half-bloom, soft dough, maturity) was recorded per plot in 3 days intervals excluding the border rows to minimize border effects on the canopy data. Normal distribution of observations was tested and two-sample t-tests for grain yield and above-ground biomass were applied.

Data collection was applied with field device using Libre Office Calc, data cleansing was done with MS Excel, and for statistical analysis SPSS from IBM was used.

Yield measurements were applied by harvesting the 4 inner rows of the repetitions excluding the border plants. After 4 weeks of sun drying, 100 g samples of grain and straw were taken and the moisture loss in a drying cabinet was used to recalibrate the grain and straw yield data summing up to the AGB.

3. Results

3.1. Distribution of Precipitation and Waterlogging

The total annual rainfall at the research site in N'Gakorou in the rural commune Cinzana in 2019 was 1088 mm which is 160% of the average precipitation of 681 mm since 1950. From sowing on 13 July 2019 to 31 October 2019, the precipitation of 887 mm was 181% of the previous year's precipitation of 492 mm during that period.

The last precipitation effectively surpassing daily evapotranspiration occurred on 20 September 2019, which was at the beginning of grain filling. Therefore, in the irrigation treatment 20 mm of water were applied with watering cans in October (10 and 30 October 2019).

An excessive precipitation event of 85 mm was recorded on 16 August 2019 followed by 73 mm on 24 August 2019 (Figure 3). The longest period of waterlogging occurred from 1 to 21 September 2019, where waterlogging is defined as saturated topsoil. The longest period of inundation was from 16 to 18 September, where inundation means that the whole experiment area was covered by visible surface water. Comparing soil moisture at 33 cm under the different cultivars during inundation and at harvest, no significant cultivar effects were identified. No severe morphological water stress signs were observed.
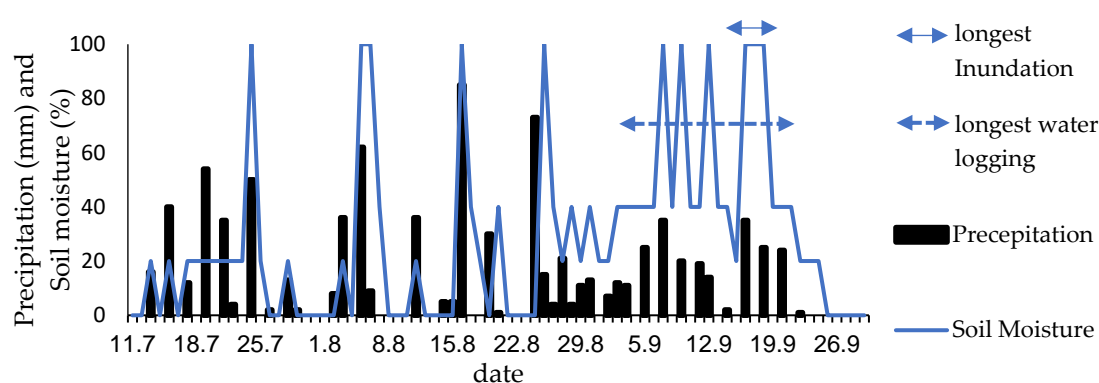
Figure 3. Inundation, waterlogging, and precipitation on experimental plots. Bright blue = Precipitation in mm day^{-1}. Visual Soil moisture assessment is presented in %(volumetric): 20% = moist topsoil, 40% = saturated topsoil with water in plow lines, 100% = inundation. Cultivar effects were insignificant.

3.2. Sorghum Above-Ground Biomass Production and Yield

In general, the late irrigation treatments during grain filling had no significant effect on grain yield and total above-ground biomass (AGB) at harvest except for AGB for the local cultivar "Gnofing" (Table 2). This cultivar, with the best AGB performance at harvest without additional irrigation during grain filling, showed rather a negative effect of irrigation on AGB. Because in AGB I (irrigated) one repetition was abandoned, the SD (observed Standard deviation) value is higher than in the non-irrigated plots for "Jakumbè". Even though data were collected under field conditions, the Standard deviation is very low especially for the grain harvest of "PR3009B" without and the AGB of "Gnofing" with irrigation.

Besides, there was neither for grain yield nor for above-ground biomass a significant effect of additional irrigation during grain filling. Plant stress assessments on yellow leave surface, leaf senescence, or plant mortality did not indicate severe waterlogging effects in all treatments.

The same applies for plant height (Table 2) and phenological stages (Figure 4). Therefore, the entire data set was used to analyze the cultivar effects only (Figure 3).

Table 2. Sorghum grain yield and above-ground biomass (AGB) of different cultivars in N'Gakoro 2019. Sowing date: 13 July 2019, Harvest: 31 October 2019.

	Grain Yield (t ha^{-1})		AGB Yield (t ha^{-1})		Canopy Height (cm)	
	NI	I	NI	I	NI	I
"Gnofing"	2.13 ± 0.36	1.80 ± 0.46	14.65 [a] ± 0.18	11.21 [b] ± 0.06	439.00 ± 45.00	413.00 ± 11.62
"Jakumbè"	2.15 ± 0.62	2.48 ± 0.62	10.87 ± 0.66	11.94 ± 1.22	433.00 ± 21.11	412.50 ± 23.59
"PR3009B"	1.62 ± 0.02	1.78 ± 0.02	6.86 ± 0.84	8.70 ± 0.39	271.42 ± 30.35	274.83 ± 36.62

N (No. of repetitions) = 3 except I N = 2. NI = No irrigation, I = irrigated with 20 mm during grain filling. a, b = significant irrigation effect for p = 0.05, all other differences between irrigation treatments were not significant.
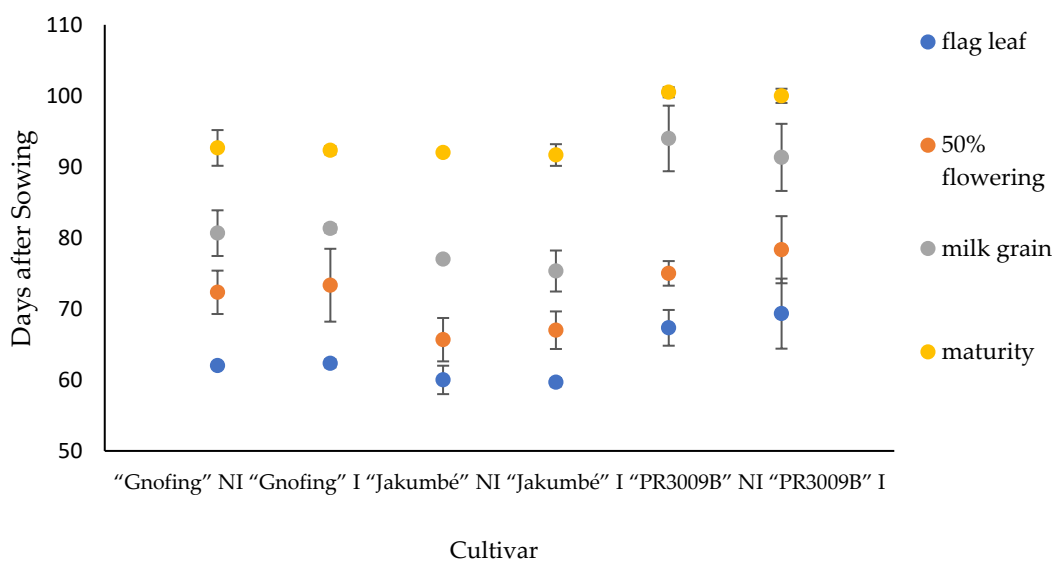
Figure 4. Phenological Development of Different Cultivars in N'Gakoro in 2019. Sowing date: 13 July 2019. Waterlogging from DaS 52 to 72. Irrigations (I) at DaS 79 and 89. NI = no irrigation (rainfed), I = additional 2 × 20 mm during grain filling. N (no. of repetitions) = 3

When using the entire data set to analyze cultivar effects, "Gnofing" showed an average maximum plant height of 4.26 m compared to "Jakumbè" 4.03 m and "PR3009B" 2.48 m. The improved landrace "Jakumbè" produced the highest grain yield, indicating that this cultivar had high tolerance to the waterlogging conditions. It had significantly higher grain yield than the hybrid cultivar "PR3009B", although the hybrid was bred for high grain yield and high harvest index (Figure 4).

Regarding AGB, the local cultivar "Gnofing" showed the highest productivity despite prolonged waterlogging around flag leaf stage (Figure 5). The difference to the hybrid "PR3009B" was significantly higher for both "Jakumbè" and "Gnofing". The local cultivar "Gnofing" yielded significantly higher AGB than "PR3009B" which was bred for low stover biomass and high harvest index (HI$_{PR3009B}$ = 0.22 > HI$_{Jakumbè}$ = 0.21 > HI$_{Gnofing}$ = 0.15).
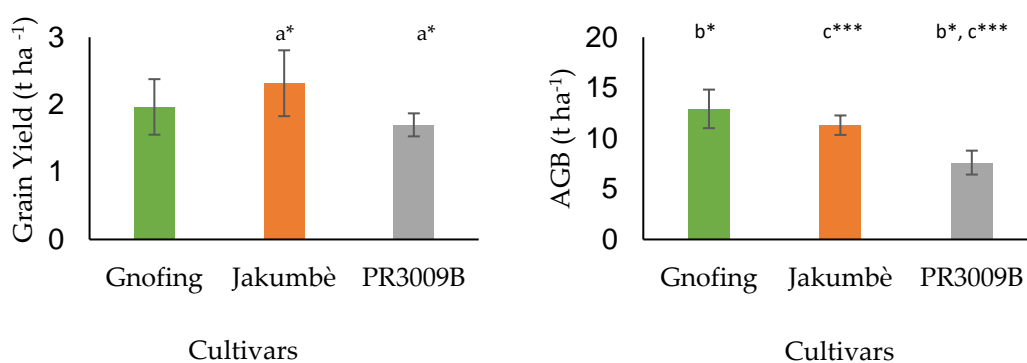
Figure 5. Grain yield and above ground biomass (AGB) of different sorghum cultivars in 2019 in N'Gakoro. n (no. of repetitions) = 5. Error bars = Standard Deviation. Two sample t-tests assuming unequal variances letters over cultivar mark significantly different relations between the both marked cultivars $0.01 \leq p < 0.05$: *, $0.001 \leq p < 0.01$: **, $p < 0.001$: ***.

4. Discussion

4.1. Irrigation Effects

According to the Food and Agriculture Organization of the United Nations (FAO), Sorghum is highly responsive to irrigation including additional water during grain filling [19]. Based on Farah et al. [30], it was expected that additional irrigation during grain filling would increase grain yield, but not above the previously recorded yield values from years with sufficient precipitation [17]. However, additional irrigation during grain filling did not improve grain yield in neither of the sorghum cultivars. It is most likely that, after the waterlogging period, the water stored within the root zone was sufficient to sustain optimal water supply during grain filling even in the treatment without additional irrigation (NI). In contrast, it seems that total above ground biomass production was slightly reduced in the local cultivar "Gnofing" when additional water was applied during grain filling. This could be due to a prolongation of soil moisture conditions close to the saturation point in the late irrigation plots and consequently lower nitrogen mineralization to sustain the standing live biomass. As "Gnofing" had produced the highest total biomass at the beginning of grain filling among the three cultivars, it was most susceptible to lack of mineral nitrogen with subsequent loss of leaves due to accelerated senescence.

4.2. Waterlogging Effects

With the effects of waterlogging through decreased root respiration, less plant available nitrogen due to reduced activity of aerobic bacteria and possible iron toxicity, reduced biomass production, and grain yield were expected. However, in 2007, the cultivar "Jakumbè" was grown under 903 mm precipitation at Cinzana with different sowing densities [31]. Depending on the plant density, grain yield ranged from 1.9 t ha^{-1} with a sowing density of 69,000 plants ha^{-1} to 2.5 t ha^{-1} grain yield with 133,000 plants ha^{-1}. When interpolating to the planting density in this paper, grain yield was about 2.0 t ha^{-1}. Thus, compared to optimal water supply in 2007 with a total precipitation of 200 mm above the isohyet of the variety [17,32] and no evidence of waterlogging, "Jakumbè" produced 16% higher grain yield under waterlogging conditions in 2019, although, nitrogen fertilizer application was higher (100 kg ha^{-1} DAP and 200 kg ha^{-1} Urea). At the University of Newcastle (UK) a pot experiment was applied at 13–26 °C with four sorghum cultivars exposed during 8–10 leave stage to 20 days of waterlogging. In this case, 20 days of inundation caused on average 30% yield reduction including reduction of root material [32]. The in-situ experiment in 2019 is opposing these findings in pot experiments under controlled conditions at least for the cultivars "Jakumbè". Differences in soil composition, root development in pots compared to in-situ conditions, and different relative humidity under controlled conditions can be discussed as possible reasons for the differences between

in-situ experiment in Mali and pot experiments in Newcastle. In another experiment in Shenyang in China, pots were put into the soil under a mobile shelter. The study of photosynthetic reactions on water stress observed increased AGB and plant height. In its findings it describes increased aerial root production and lower Chlorophyll a content in the leaves and decreased stomata conductance and decreased transpiration. The effect is lower than under drought stress [28].

Furthermore, the difference of air- and soil temperature can be discussed. At cloudy days, the plants are less stressed by high air temperatures and by surface moisture evaporation and during flooding water surface reflection the soil temperature is decreased. In 2019 less days of cloud coverage occurred after the core rain season ending on 25 September than in previous years. The thermal time sum of a year with high precipitation sums due to erratic rainfall in the core rainy season can therefore not generally be below an average years' time sum. In the given climatic context, heat stress connected to drought stress is an issue. Under excessive water, aerial processes are affected but temperatures do not drop below basal growth temperatures.

According to the breeders, potential yield of "Jakumbè" is 2.5 t ha^{-1} [17]. Hence, "Jakumbè" reached the yield potential in 2019 under prolonged waterlogging with late irrigation, indicating the superior tolerance of this cultivar to waterlogging. The unexpected positive performance of "Jakumbè" proves its tolerance to long periods of waterlogging including several days of inundation in situ. The harvest index was lower than of the hybrid cultivar but both grain yield and biomass production were significantly higher.

It is very likely that the yield potential of "Gnofing" as a local cultivar is similar or even lower than the yield potential of "Jakumbè" (Table 2). Hence, most probably, "Gnofing", which produced similar grain yield in 2019 as "Jakumbè", also reached high grain yields despite the long period with waterlogged soil. It can be therefore also considered as highly tolerant to waterlogging.

With respect to AGB and plant height, the cultivar "Jakumbè" produced in 2019 under waterlogged conditions 42% more AGB than in 2007 and plants were 80% higher than in 2007 [31]. The increased above ground biomass of "Jakumbè" in 2019 supports the theory that biomass is increasing with the cumulative precipitation [30,31]. The same holds for the local cultivar "Gnofing", which produced significantly more AGB compared to "Jakumbè" under prolonged waterlogging in 2019, while grain production was not significantly lower than for "Jakumbè" [31].

5. Conclusions

Our study indicates that in a context of rapidly growing corn production which is susceptible to several days of inundation and annual total precipitation below 600 mm, sorghum qualifies as a buffer in extreme years which are expected to increase in the new millennium.

At larger scales, climate-smart techniques such as sorghum cultivars tolerant to waterlogging combined with ridging tillage can reduce the impact of inundations which affected 1.729 households in 2019 [7] because of extreme downpours.

This participatory field research in the context of the climate-smart village approach is a first step to fill a knowledge gap on increasingly wet rain seasons with higher probability of waterlogging according to CMIP5 future climate scenarios. Valuable findings opposing in vitro research have been gathered, motivating further research in adaptation to waterlogging and valuing farmers contributions to breeding cultivars with resistance to intra-seasonal droughts as well as waterlogging. Climate-smart agricultural practices like ridging tillage demand research on dual purpose functionality for both weather extremes. Continued efforts are needed in research to provide extension service advice addressing the growing population pressure and being adopted for simultaneously dry and wet phases.

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