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PAPER

Maize response to temporary floods under ambient on-farm conditions of the West African Sahel

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Abstract

With the ongoing global warming, the occurrence and amplitude of extreme weather events have increased over the West African Sahel. The increasing frequency of heavy rain events, can negatively affect the lowland crops' growth and production. Two-season field experiments were conducted near Ouagadougou (Burkina Faso) to test the effects of temporary flooding and surface water stagnation on maize (*Zea mays L.*) growth and productivity. The treatments were organized into a split-split plot design. Three factors were monitored, including aboveground flooding levels (i.e., 0 cm, 2–3 cm, and 7–8 cm), flooding duration (i.e., three days and six days), and growth stages (i.e., six-leaf stage (V6), tasseling stage (VT) and milky stage (R3)). Optimal crop management was practiced to *Obatanpa* cultivar planted during the rainy season and flooding was induced by over-irrigation. The results show that three days and six days of flooding, reduced grain yield by at least 35% when they occurred at the tasseling stage. Only 4–6 days of flooding reduced grain yield by 21% at the six-leaf stage. Further scrutiny, using the stress day index (SDI), revealed that the penalty on yield increases exponentially under flooding conditions as the value of the stress day index increases. Considering the new characteristics of the rainfall regime in the West African Sahel, dominated by a high frequency of heavy rain events and wet spells, temporary floods, and water stagnation are tremendously contributing to yield loss of on-farm maize. As the region's climate changes, we hypothesize that excess water stress will become the next cause of food insecurity in the area.

1. Introduction

Rainfall variability has increased over the West African Sahel with the ongoing global warming. Besides the erratic intra-seasonal distribution of rain events leading to mixed (wet-dry) patterns of the rainy seasons (Salack *et al* 2016), the amplitude and the frequency of heavy rain events have significantly increased (Taylor *et al* 2017, Salack *et al* 2018) as well as wet spells (Bichet and Diedhiou 2018), showing a glimpse of what the future rainfall regime may look like. According to climate projections, rainfall intensity may likely increase in the region (Sylla *et al* 2015). This trend of the regional climate will bring more complexities to rainfed cropping systems management.

So far, the most documented abiotic constraints for cereals, among the staple crops of the Sahel, have been low soil fertility and drought (Badu-Apraku and Fakorede 2017). The stress due to excess water, which results in soil waterlogging, flooding, and water stagnation, is underestimated, even though it is among the most severe constraints affecting lowland crops' growth, development, and production (Ren *et al* 2014). Waterlogging occurs whenever the soil moisture reaches saturation. Still, there is no free water layer to accumulate, while flooding is a phenomenon in which a water layer with a certain height appears and remains for some time on the soil surface (Tian *et al* 2020). Both cases cause inadequate root respiration and plant photosynthesis. They are potentially harmful to certain cereal crops such as maize and millet, which are critical for food security in the Sahel (Tian *et al* 2019, 2020).

Heavy rain events are the leading cause of soil waterlogging, flooding, and water stagnation. They amplify erosion of arable land in high runoff areas and soil nutrients leaching and fungal infestations of some crops (Rosenzweig *et al* 2001, Salack *et al* 2015, Guan *et al* 2015). Soil waterlogging stress affects 12% of the world's growing areas (Shabala 2011, Xu *et al* 2013). This risk increases at some locations in West African zones due to the increased occurrence of heavy rain events (Salack *et al* 2018).

Widely cultivated on smallholder farms in West Africa, maize covers around 25 million hectares, producing 38 million tons of grain annually. It is grown primarily for food and accounts for 20% of the calorie intake of 50% of the population (Smale *et al* 2013, Badu-Apraku and Fakorede 2017). Maize plants have no naturally occurring air spaces in their roots; therefore, with a gradual decline in soil oxygen, the plant suffers from hypoxia (low oxygen) followed by anoxia (no oxygen) when they are exposed to prolonged soil moisture exceeding 80% of the field capacity (Zaidi *et al* 2003, Ren *et al* 2016). Often, the early seedling, the knee-high, the tasseling, and the milk stages are the most critical crop growth stages tested during the selection of maize cultivars capable of withstanding excessive soil moisture conditions (Zaidi *et al* 2004, Liu *et al* 2010). From experiments conducted in China, Li *et al* (2011) showed that more than three days of waterlogging can decrease the maize yield by 40%. Tian *et al* (2019) found that the grain yield can reduce by 65%-80% with nine days of waterlogging at the seedling stage, but this duration has no significant adverse effect at the tasseling stage. When waterlogging occurs around the flowering stage, the grain yield can be suppressed because of the shortened grain filling duration (Yang *et al* 2016). Apart from the yield loss, the plants' survival rate is also used to select the crop varieties according to their tolerance to excessive soil moisture (Estebana, Solilap 2016).

Most of these findings and conclusions were drawn from experiments conducted in pots (Yang *et al* 2016, Kaur *et al* 2019, Otie *et al* 2019), lysimeters, and greenhouse enclosures (Lizaso and Ritchie 1997, Zugui *et al* 2013). Very few experiments were conducted under field conditions (Ren *et al* 2014, 2016, Tian *et al* 2019), and almost none were implemented in the ambient environmental realities of the West African semi-arid regions. In this study, we tested and provided further insights on the effects of temporary flooding and surface water stagnation on the growth, development, and production of *Obatanpa* maize cultivar in ambient on-farm conditions of the West African Sahel.

2. Methods

2.1. Site description

The West African Sahel is the region that stretches from the East of Lac Chad to the West Coast of Senegal, between latitudes 10°N to 20°N, covering thereby the whole country of Burkina Faso. In this region, the rainy season is dominated by the West African monsoon. The large-scale patterns show onset in May-June and cessation in September-beginning of October with 95%–99% of the annual rainfall volume distributed across June-July-August-September. Our investigations were conducted during the 2017 and 2018 rainy seasons, at Boassa (12°16'56.6'N, 1°36'14.1'W), in the suburb of Ouagadougou, the capital city of Burkina Faso (supplementary, figure S1 (available online at stacks.iop.org/ERC/4/045004/mmedia)). The analysis of the topographic patterns on the contour map (Figure S2) shows that the elevations vary from 311.80 m (at the north-western part of the field) to 311.20 m (at the south-eastern part of the field). This pattern drives the direction of runoff flow (Figure S2).

During the experiments, every 10 min, weather variables such as solar radiation, maximum and minimum temperatures, relative humidity, wind speed, and rainfall were collected using an automatic weather station installed on-site. The site had similar climatic conditions as Ouagadougou, with 841.6 mm and 795.4 mm total rainfall recorded between May-October, and the average temperature was 35 °C and 37 °C in 2017 and 2018, respectively. The maximum daily temperature recorded in May was 41.5 °C in 2017 and 43.6 °C in 2018. The monthly relative humidity varied from 19%–76% in 2017 and 19%–82% in 2018. The total potential evapotranspiration was lowest in August (157 mm and 160 mm) but reached its maximum in March (322 mm and 315 mm) for 2017 and 2018.

The treatments were set-up, on an imperfectly drained, eutric gleyic fluvisol, more profound than 120 cm. Fluvisols occur on materials deposited in aqueous sedimentary environments, such as inland fluvial and lacustrine fresh-water environments, marine environments, and coastal salting or brackish marsh environment, of which deltas are a particular case. They cover an estimated area of over 350 million hectares worldwide. In West Africa, they cover a vast area in Senegal, Gambia, Guinea Bissau, Sierra Leone, Liberia, the Volta basin, and the Niger Delta (supplementary, figure S3). On our experimental site, the upper soil layer (29 cm) was dark grey with a silty-sandy texture. From 29 cm to 70 cm depth, the layer was brown with sandy-clay texture and

Table 1. Description of the treatments implemented at the experimental site of Boassa.

Treatment	Description
CK	control with barriers, representing the aboveground water level of 0 cm applied during 3 or 6 days at the six-leaf, tasseling or milky stages. There was no irrigation for this treatment.
T2D3V6	water level at 2-3 cm applied 3 days at the six-leaf stage
T2D3VT	water level at 2-3cm applied 3 days at the tasseling stage
T2D3R3	water level at 2-3cm applied 3 days at the milky stage
T2D6V6	water level at 2-3cm applied 6 days at the six-leaf stage
T2D6VT	water level at 2-3cm applied 6 days at the tasseling stage
T2D6R3	water level at 2-3cm applied 6 days at the milky stage
T7D3V6	water level at 7-8 cm applied 3 days at the six-leaf stage
T7D3VT	water level at 7-8cm applied 3 days at the tasseling stage
T7D3R3	water level at 7-8cm applied 3 days at the milky stage
T7D6V6	water level at 7-8cm applied 6 days at the six-leaf stage
T7D6VT	water level at 7- 8cm applied 6 days at the tasseling stage
T7D6R3	water level at 7-8cm applied 6 days at the milky stage

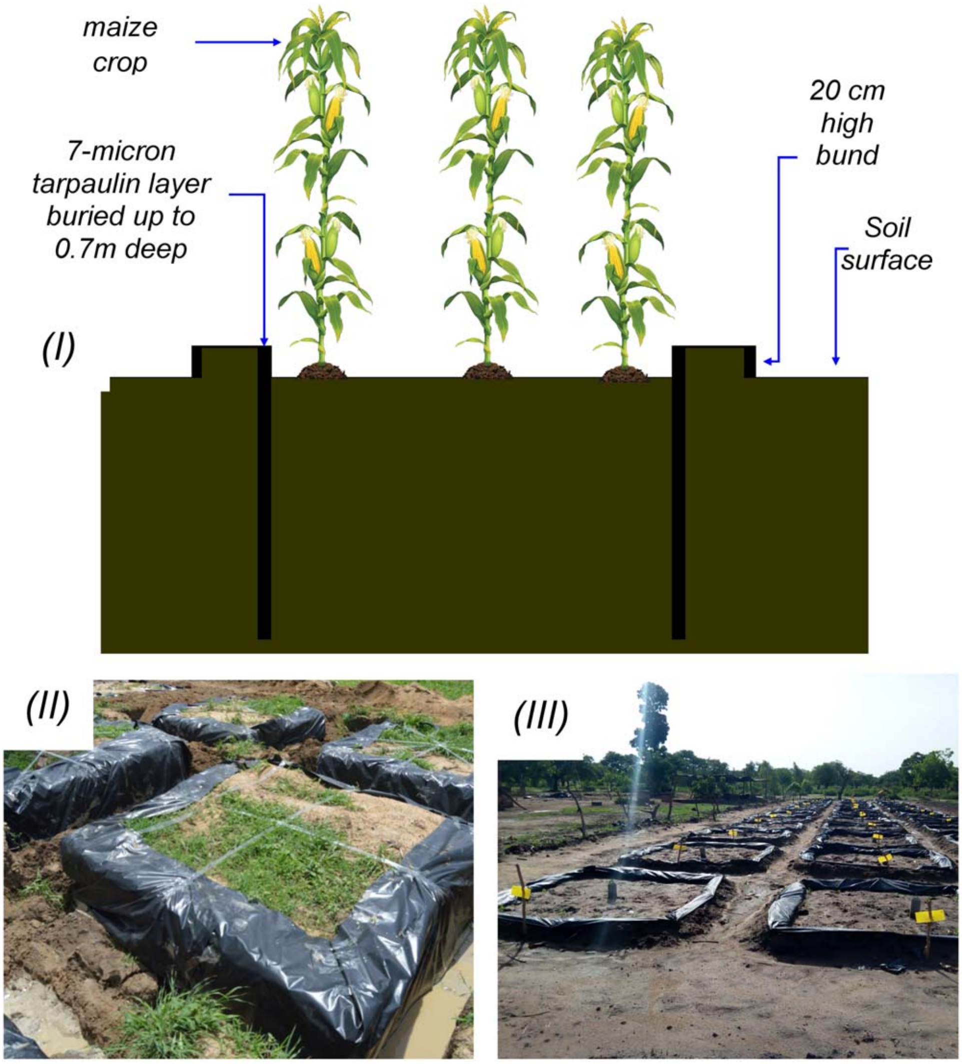

Figure 1. Sketch a plot unit set-up of the experimental design in 2017 and 2018 (I) at Boassa experimental station. (II) Upper view of the plot unit and (III) Facial of plots layout.

Table 2. Cropping calendar and crop management practices during 2017 and 2018 at Boassa experimental site.

Crop management	Dates 2017	Dates 2018	Characteristics of the operation
Tarpaulin setting-up	22 Jun	30 May	
Bunding	6 Jul	25 Jun	
Manual plough	6 Jul	27 Jun	
Sowing	8 Jul	17 Jul	62500 plants. ha^{-1}
First manual weeding	17 Jul	29 Aug	
First fertilization	26 Jul	8 Aug	625 kg. ha^{-1} of NPK 20-10-10
Second manual weeding	3 Aug	7 Sep	
Flooding at jointing stage	11 Aug	18 Aug	
First pest control	15 Aug		6 ml. ha^{-1} PYRINEX QUICK 212 EC containing 12 g.l^{-1} of Deltamethrin and 200 g.l^{-1} of Chlorpyrifos
		29 Aug	21.13 g. ha^{-1} EMACOT 50WG containing Emamectin benzoate at 19 g.l^{-1}
Third manual weeding	22 Aug	30 Sep	
Second fertilization	27 Aug	7 Sep	62.5 kg. ha^{-1} of Urea (46% N)
			375 kg. ha^{-1} of Ammonium sulphate (21% N)
Flooding at tasseling stage	30 Aug	8 Sep	
Second pest control	6 Sep		8 ml. ha^{-1} PYRINEX QUICK 212 EC containing 12 g.l^{-1} of Deltamethrin and 200 g.l^{-1} of Chlorpyrifos
		1 Sep	21.13 g. ha^{-1} EMACOT 50WG containing Emamectin benzoate at 19 g.l^{-1}
Fourth manual weeding	25 Sep		
Third pest control	25 Sep		12 ml. ha^{-1} PYRINEX QUICK 212 EC containing 12 g.l^{-1} of Deltamethrin and 200 g.l^{-1} of Chlorpyrifos
Flooding at milky stage	29 Sep	25 Sep	
Pest treatment	30 Sep		12 ml. ha^{-1} PYRINEX QUICK 212 EC containing 12 g.l^{-1} of Deltamethrin and 200 g.l^{-1} of Chlorpyrifos
Harvest	14 Oct	20 Oct	

contained yellow-brown particles from redox reactions. The supplementary table S1 provides other detailed soil profile characteristics up to 120 cm depth.

2.2. Experimental design and treatments

A split-split plot experimental design was set up with three replications, 13 randomly distributed treatments of 6.76 m^2 each. The factors considered were three aboveground water levels (i.e., 0 cm, 2–3 cm, and 7–8 cm), two flooding durations (i.e., three days and six days,) and three maize growth stages (i.e., six-leaf or jointing stage (V6), tasseling stage (VT), milky stage (R3)) of the *Obatanpa* cultivar. The experimental design included one non-flooded control (i.e., a relative control plot with plastic tarpaulin barrier (CK) representing 0 cm of water level applied during 3 or 6 days at the three growth stages). Table 1 provides details on the treatments.

A 7 microns black plastic tarpaulin was buried from the surface to 70 cm depth. It was combined with 20 cm height bunds (figure 1(a)) to induce stagnation and avoid runoff and lateral advection of water during the flooding periods. Manual plowing was used to construct the bunds. The plots were separated by 100 cm as an inter-plot spacing (figure 1(b), (c)).

Over-irrigation was applied to the plots using a solar-powered borehole to pump underground water into three graduated water tanks of 1 m^3 capacity (supplementary figure S4(a), (b)). Each water tank was linked to the plots with a network of polyvinyl chloride (PVC) pipes of 10 cm in diameter. The installed valves at the end of the pipes and the graduation on the water tanks were used to measure the amount of water used for irrigation (supplementary figure S4(c), (d)).

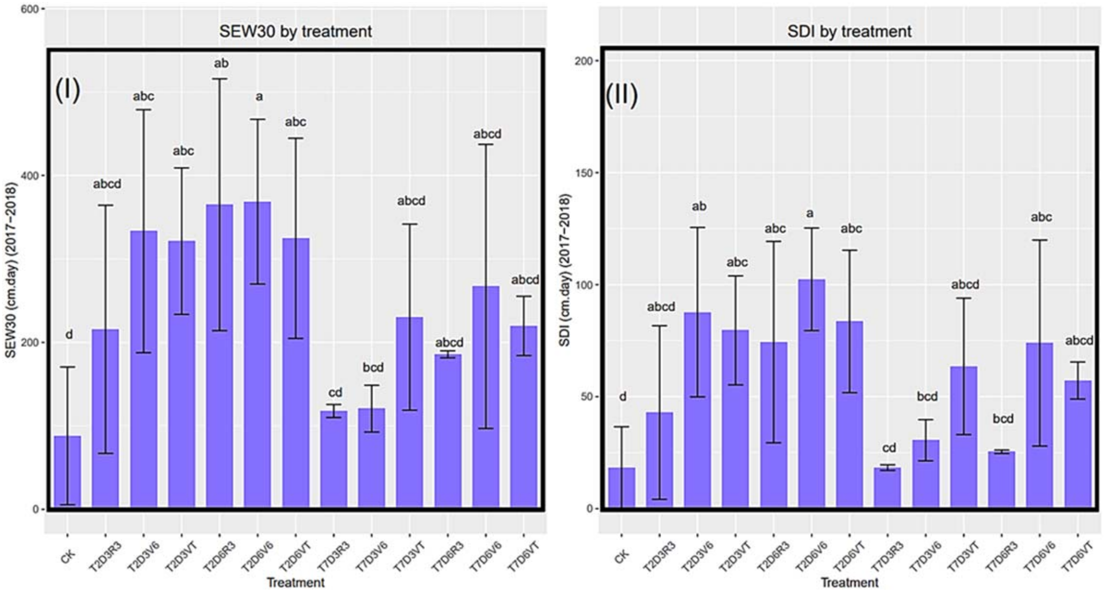

Figure 2. Excess water stress factor (SEW30) (I) and Stress-Day Index (SDI) variation by treatment (II). Bar charts topped with the same letter showed no significant difference at 95% confidence interval according to Tukey's Multiple Range Test. Standard deviations are indicated by the error bars.

2.3. Data sampling and analysis

Optimal crop management practices, including field operations, dates, types, and rates of pesticide and fertilizer, were applied during the experiments. The technical itineraries applied are summarized in table 2. The daily water table in the 30 cm topsoil was regularly recorded through piezometers installed in the center of each plot. This water table data is used to estimate the stress-day factor (SEW30), following equation (1) (Kanwar *et al* 1988, 1998, Evans and Skaggs 1984):

$$\mathrm{SEW30} = \sum_{i}^{n} (30 - WTD_i) \tag{1}$$

where n is the number of days ($i = 1, 2, \ldots n$) and WTD_i is the water table depth (in cm) in the 30 cm topsoil on the day i. In this estimation, the depth of the water table is zero for the days when the water table is above the soil surface. SEW30 is defined as the sum of excess water that occurs each day in the primary root zone of the top 30 cm soil layer (Setter and Waters 2003). Hence, SEW30 values expressed in 'cm.day' quantify the excessive soil water conditions.

The stress-day index (SDI) concept quantifies in cm.day, the cumulative stress of wetness on the maize plant during the growing season following equation (2) (Kanwar 1988):

$$\mathrm{SDI} = \sum_{j}^{m} (CS_j \times SD_j) \tag{2}$$

Where m is the number of growth stages, CS_j values are normalized crop susceptibility factors for stage j, and SD_j is a stress-day factor for stage j in cm.day. supplementary table S2 provides the normalized maize susceptibility factors for each growth stage.

From 30 days after sowing (DAS), maize vegetative material was sampled every 15 days on a set of 5 randomly selected plants. This vegetative material is used to observe the crop growth and development parameters (e.g., plant height, leaf length, width, tasseling and flowering stages) and derive another variable such as the leaf area index (LAI). A ribbon meter graduated in millimeters was used to measure the plant height from the collar to the apex of the meristem. The green leaf length and maximum width were measured with a ruler from its sheath to its tip and at mid-length of the leaf, respectively. The leaf area (LA) was calculated following equation (3):

$$LA = Leaf\ \ length * maximum\ \ width * k \tag{3}$$

where k is a shape factor with the value of 0.75 and the maximum width represents the highest value of width at the time of measurement. LAI was calculated as the ratio of LA to the horizontal soil surface area occupied by each planting hill (Ren *et al* 2014).

Without any effect on the experiment, aboveground biomass was also collected by destructively sampling, on the specific lines, from two planting holes per plot, at 48 DAS, 68 DAS, and harvest. Then, biomass samples were dried in an oven at 70°C for 72 h to determine the accumulated dry aboveground biomass in 2017 and

Table 3. Variation of the height, the leaf area index, and the flowering stage of *Obatanpa* cultivar under different treatments

Treatments[a]	Height (cm)					Leaf area index		Flowering stage (DAS [b])
	30 DAS	45 DAS	60 DAS	75 DAS	30 DAS	60 DAS	75 DAS	
CK	84.12 ± 5.51 *b*	180.24 ± 5.19 *abc*	241.32 ± 3.9 *ab*	240.93 ± 4.66 *ab*	1.04 ± 0.12 *a*	4.7 ± 0.45 *ab*	3.42 ± 0.99 *ab*	51.92 ± 0.74 *bc*
T2D3R3	94 ± 9.99 *ab*	189.46 ± 2.27 *abc*	246.88 ± 9.69 *ab*	248.87 ± 10.32 *ab*	1.04 ± 0.2 *a*	4.67 ± 0.2 *abc*	3.08 ± 1.26 *ab*	53.17 ± 0.58 *ab*
T2D3V6	95.6 ± 8.47 *ab*	163.11 ± 17.98 *bcd*	219.18 ± 30.21 *b*	227.2 ± 16.81 *b*	1.29 ± 0.36 *a*	4.75 ± 0.56 *ab*	3.17 ± 1.13 *ab*	51.5 ± 1.32 *bc*
T2D3VT	90.12 ± 19.05 *ab*	184.46 ± 21.06 *abc*	238.39 ± 16.87 *ab*	235.9 ± 7.48 *ab*	1.08 ± 0.16 *a*	3.8 ± 0.43 *bcd*	2.79 ± 0.58 *ab*	51.67 ± 1.44 *bc*
T2D6R3	91.69 ± 9.13 *ab*	197.52 ± 18.62 *ab*	241.27 ± 16.35 *ab*	245.57 ± 8.26 *ab*	1.34 ± 0.18 *a*	5.09 ± 0.46 *a*	3.16 ± 1.09 *ab*	50 ± 2.5 *bc*
T2D6V6	89.44 ± 7.25 *ab*	137.37 ± 15.49 *d*	184.27 ± 23.86 *c*	181.2 ± 29.67 *c*	1.15 ± 0.16 *a*	3.56 ± 0.87 *cd*	2.61 ± 1.61 *b*	55.17 ± 1.44 *a*
T2D6VT	86.21 ± 6.07 *ab*	174.63 ± 7.34 *abcd*	233.93 ± 11.81 *ab*	237.17 ± 18.89 *ab*	"1.1 ± 0.15 *a*	3.11 ± 0.98 *d*	2.66 ± 0.9 *b*	52.33 ± 0.58 *abc*
T7D3R3	102.24 ± 2.85 *ab*	203.74 ± 10.96 *a*	257.52 ± 14.34 *a*	261.37 ± 7.81 *a*	1.31 ± 0.37 *a*	5.11 ± 0.6 *a*	4.01 ± 1.04 *ab*	51.08 ± 0.38 *bc*
T7D3V6	107.91 ± 17.91 *a*	184.22 ± 24.13 *abc*	242.06 ± 10.38 *ab*	237.97 ± 13.15 *ab*	1.34 ± 0.41 *a*	5.2 ± 0.38 *a*	4.12 ± 0.69 *ab*	49.67 ± 3.4 *c*
T7D3VT	104.44 ± 11.65 *a*	194.61 ± 14.18 *abc*	251.99 ± 5.64 *ab*	247.87 ± 5.65 *ab*	1.37 ± 0.58 *a*	4.56 ± 0.71 *abc*	2.59 ± 1.4 *b*	50.83 ± 1.53 *bc*
T7D6R3	86.08 ± 0.96 *ab*	172.81 ± 7.99 *abcd*	250.1 ± 16.19 *ab*	247.93 ± 11.07 *ab*	1.07 ± 0.08 *a*	5.26 ± 0.48 *a*	4.22 ± 0.9 *ab*	51.83 ± 0.76 *bc*
T7D6V6	87.48 ± 10.35 *ab*	156.78 ± 21.54 *cd*	219.55 ± 8.7 *b*	219.13 ± 5.97 *b*	1.08 ± 0.37 *a*	4.38 ± 0.23 *abc*	4.61 ± 0.8 *a*	52.5 ± 1 *abc*
T7D6VT	92.17 ± 18.87 *ab*	187.75 ± 28.26 *abc*	244.96 ± 19.33 *ab*	242.2 ± 22.22 *ab*	1.07 ± 0.27 *a*	3.68 ± 0.73 *bcd*	2.4 ± 0.55 *b*	51.67 ± 2.08 *bc*

[a] Treatments are described in table 1.

[b] day after sowing; averages values ± standard deviations followed by the same letter within the same column showed no significant difference at 95% confidence interval according to Tukey's Multiple Range Test.

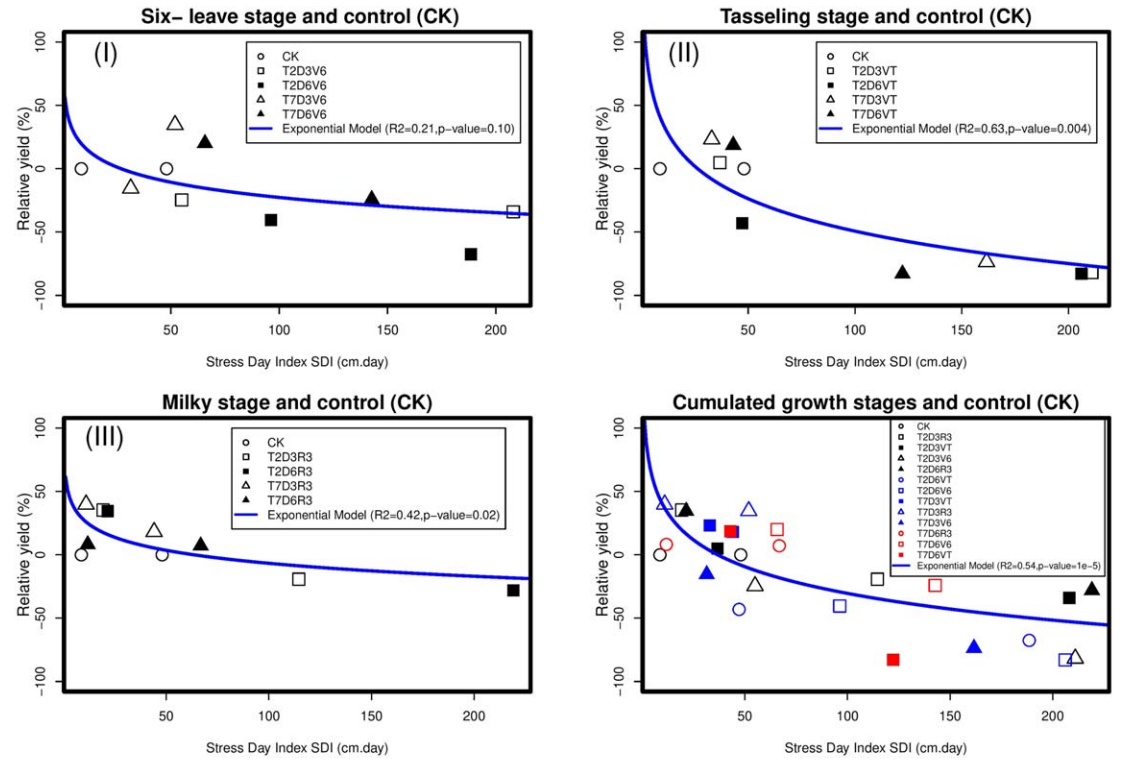

Figure 3. Relationship between Stress Day Index (SDI) and maize (*Obatanpa* cultivar) yield loss in case of flooding at the six-leaf stage (I), at the tasseling stage (II) at the milky stage (III), and the overall relationship considering all the three phenological stages (IV).

2018. After the physiological maturity, except for the ears on the borderlines and the plants' lines targeted for the aboveground biomass samples, all other ears were harvested, and the harvested plants were counted. After being dried under sunlight for 15 days, the ears were weighted and determined the grain yield. The weight of the grain yield per treatment was the input for estimating the relative yield loss (RYL) following equation (4)

$$RYL = 100 \times \frac{Y_{TR} - Y_{CK}}{Y_{CK}} \tag{4}$$

Y_{CK} is the grain yield from the relative control treatment with barriers (CK), and Y_{TR} is the grain yield of each of the other treatments.

The analysis of variance (ANOVA) was performed for the excess water stress-day factor (SEW30), the stress day index (SDI), the height, the leaf area index (LAI), the flowering stage, the aboveground biomass, and grain yield observed during the 2-year experiment (supplementary table S3). We used the 'agriciolae' package built for R software (De Mendiburu 2020), and comparisons among different factors and treatments were based on the Tukey Multiple Range test at a 95% confidence interval ($p \leqslant 0.05$).

3. Results

3.1. Soil water dynamics and excess water stress

During the 2-year experiment, the 2–3 cm and 7–8 cm flooding depths above the soil surface were induced using average amounts of water worth 145.5 mm/day and 210.3 mm/day (at V6 stage), 139 mm/day, and 175.6 mm/day (at VT stage) and 156.3 mm/day to 176.3 mm/day (at R3 stage). The excess water caused different water level dynamics per treatment which were translated into excess water stress indices (figure 2). Due to the fluctuation of the water level in the topsoil with the rainfall events of the seasons, the natural soil waterlogging was highly dependent on the field topography. Indeed, the water dynamics in the topsoil of the control plots have shown a variation of level according to the slope with 9.5% probability to observe water level in this topsoil at downhill compared to 3.5% probability to observed the same on plots located uphill (supplementary figure S5). In the 30 cm topsoil, the daily water level fluctuations converted into excess water stress-day factor (SEW30) and stress-day index (SDI) showed uniform distribution of excess water stress across replications. Compared to the control plots having 88 cm.day, SEW30 increased significantly when the plots were flooded at VT (323 cm.day) and V6 stages (351 cm.day) at 2–3 cm aboveground. With the increase in the duration of water stagnation, SEW30 and SDI of 6-day flooded plots were significantly higher than the control plots. SEW30 and SDI

Table 4. Aboveground biomass and grain yield variations of *Obatanpa* cultivar during the experiment

Treatment[a]	Aboveground biomass (kg. ha^{-1})		
	48 DAS[b]	68 DAS	94 DAS
CK	3000.0 ± 991.7 *ab*	17309.1 ± 3009.0 *ab*	15196.8 ± 5546.2 *abc*
T2D3R3	2656.2 ± 870.0 *ab*	16276.5 ± 5088.5 *abcd*	13754.2 ± 3229.1 *abcd*
T2D3V6	2420.1 ± 798.5 *ab*	10203.1 ± 3147.0 *cd*	11612.3 ± 4562.4 *cde*
T2D3VT	2562.5 ± 1299.0 *ab*	13097.2 ± 4219.8 *abcd*	8483.5 ± 742.1 *ef*
T2D6R3	3142.4 ± 1413.6 *ab*	17179.7 ± 236.7 *abc*	14822.7 ± 5288.9 *abc*
T2D6V6	1909.7 ± 318.2 *b*	9102.1 ± 4609.7 *d*	6843.3 ± 3229.2 *f*
T2D6VT	3506.9 ± 872.1 *ab*	11835.7 ± 2405.5 *bcd*	8330.3 ± 3783.8 *ef*
T7D3R3	3859.4 ± 274.7 *a*	19645.7 ± 3418.2 *a*	16924.4 ± 1442.3 *ab*
T7D3V6	2767.4 ± 427.2 *ab*	16278.5 ± 5711.5 *abcd*	16634.7 ± 4421.5 *ab*
T7D3VT	4192.7 ± 564.3 *a*	17072.1 ± 2262.2 *abc*	9262.3 ± 985.5 *def*
T7D6R3	3357.6 ± 603.5 *ab*	16691.0 ± 1344.0 *abc*	17617.9 ± 1333.5 *a*
T7D6V6	2671.9 ± 489.4 *ab*	9084.3 ± 2469.0 *d*	12751.6 ± 829.2 *bcde*
T7D6VT	2895.8 ± 1454.5 *ab*	13572.3 ± 4869.6 *abcd*	9964.1 ± 265.6 *def*

[a] Treatments are described in table 1

[b] day after sowing; averages values ± standard deviations followed by the same letter within the same column showed no significant difference at 95% confidence interval according to Tukey's Multiple Range Test.

increased considerably in the case of 2–3 cm flooding downhill compared to 7–8 cm flooding uphill (figure 2, supplementary table S4).

3.1.1. Effects of waterlogging on maize plant height, leaf area index (LAI), and flowering

The analysis of variance showed that maize plant height was significantly affected at every growth stage where the temporary flooding was induced from 45 DAS to the end of the growth cycle (table S5). Plant height was reduced by 7% at 75 DAS under a short duration of flooding at the V6 stage, and this reduction reached 11% after 6-day water stagnation. At the V6 stage, the 2-3 cm above-surface water depth has reduced the plant height by 16% and 15% at 60 DAS and 75 DAS compared to the control treatment CK (table 3). With 3 or 6 days of submersion, the reduction in LAI was at least 13% at the VT stage (60 DAS), and 10% at the V6 stage in case of 6 days of submersion (60 DAS). At 75 DAS, the LAI continued to decrease for the plants flooded at the VT stage by 16%, but for those flooded at the V6 stage, LAI was increased by 4%. The flowering dates were delayed by three days under six days flooding at the V6 stage induced by 2–3 cm aboveground (table 3 and supplementary table S5).

3.1.2. Effects of waterlogging on maize aboveground biomass and grain yield

When flooded at VT and V6, the final aboveground biomass was reduced by 27% and 14%, respectively. However, when waterlogging occurred at the R3 stage, there was a non-significant variation (+1% to +4%) in the final aboveground biomass (table 4, Table S7). The grain yield was also reduced by 35% and 7% on average, with flooding occurring at VT and V6 stages, respectively. Therefore, at least three days of water stagnation (e.g., 2–3 cm or 7–8 cm above surface water level) at the VT stage were enough to shorten the grain filling phase and have reduced the grain yield by 35%, as compared to the control treatments (table 4). But at the V6 stage, six days of submersion reduced the yield by 21%, while three days of submersion induced a 6% grain yield increase. This contrast was also observed when maize was flooded during 3 and 6 days at the R3 stage as the grain yield slightly increased by 8% and 2% (supplementary table S6).

The relative yield index (RYL) generated from equation (4) was regressed against the SDI to assess the grain yield losses concerning excess-water stress. Considering all the tested growth stages (V6, VT, and R3) and the control plot CK, an exponential negative relationship was found between the SDI and the RYL with statistically significant coefficients of determination, as shown in figure 3(a)–(d).

4. Discussion

On-farm flooding and water stagnation depend on field topography and management practices (Fu *et al* 2000, Qin *et al* 2013), soil type, drainage potential, and exposure to heavy rain events (Lim and Lee 2017, Tang *et al* 2018). Our results show that phenological traits such as flowering and plant height may be adversely affected when they occur. The delay in height growth of maize plants, observed during the 2-year ambient on-farm conditions when flooding occurred at V6 for six days, agrees with the results of Singh and Ghildyal (1980) and

Tian *et al* (2020), who noticed significant stunting for maize with the increasing duration of flooding at the V6. Knowing that plant height is constituted by internodes, the stunted growth of maize could be attributable to a reduction in the internode length under excess-water stress reported by Valerie and Moses (2016), which is the cause of plant dwarfness under this condition.

The late inception of the flowering, when maize is flooded at the jointing stage, observed during these on-farm experiments agree with Zaidi *et al* (2003), Lone and Warsi (2009), and Wang *et al* (2012). Those authors observed a delay in maize's tasseling, anthesis, and silking stages after flooding was induced at the early vegetative stages and found that disruptions in reproductive stages resulted in poor pollination, affecting the overall grain production. The meaningful LAI reductions, observed when waterlogging occurred at the VT stage, contrasted with Ren *et al* (2014), who showed that the most significant LAI reduction of 24% was observed when the waterlogging occurred during the vegetative phase (stage V3 and V6). However, when maize is flooded at the VT stage, high plant mortality, decreased total leaf number, leaf area, and dry matter accumulation were reported by Zaidi *et al* (2004) and Shah *et al* (2012).

Photosynthesis is one of the most sensitive physiological processes to water stress (Ramachandra *et al* 2004). Some studies showed that waterlogging stress damages chlorophyll and decrease the chlorophyll content. Therefore, the subsequent decline in the photosynthetic enzyme activity and the reduction in the photosynthetic rate inhibit plant growth, leaf area expansion, and biomass accumulation, ultimately resulting in a decrease in crop yield (Smethurst *et al* 2005). Our study observed a significant biomass loss when flooding occurred during the six-leaf (V6) and tasselling stages. This is aligned with Tian *et al* (2019), who reported that the effect of waterlogging stress on the dry matter accumulation of maize is greatest at the V3 stage, followed by V6 and VT.

The most considerable yield losses were experienced when water stagnation lasted at least three days during the tasseling stage (VT) and six days during the early tested vegetative stage (V6). This result contrasts with Tian *et al* (2019) and Liu *et al* (2010), who found no significant adverse effect of excessive water at the tasseling stage and more sensitivity of maize to waterlogging from the early seedling stage to the tasselling stage, respectively. However, when waterlogging occurs around the flowering stage, the grain yield can be suppressed because of the shortened grain filling duration (Yang *et al* 2016), and recently, Estebana, Solilap (2016), showed that tasselling stage was the most sensitive stage of the white maize under seven-day of waterlogging conditions. The yield loss was exponentially related to the increased stress-day index during those growth stages. This was similar to results reached by Kanwar (1988) after a similar experiment carried out in the USA.

Heavy rain events are the triggers of floods. Many people still lose their lives and properties in many parts of the West African Sahel because of floods (Salack *et al* 2018). The socio-economic costs associated with floods continue to rise due to a lack of proper detection and appreciation of the causes, impacts, and consequences of floods on the well-being of farming systems and livelihoods. In the recent past, studies have shown that the Sahelian rainfall regime is characterized by a lasting deficit of the number of rainy days while extreme rainfall occurrence is on the rise (Panthou *et al* 2018). Future projections based on climate models point towards a climate with less frequent, more intermittent, but more intense rainfall events over much of West Africa (Fitzpatrick *et al* 2020). As the West African Sahel climate changes, water stagnation, and farm inundation will be caused by the increased amplitude and frequency of heavy rain events (Taylor *et al* 2017, Salack *et al* 2018) and wet spells (Bichet and Diedhiou 2018). Our results bring more insight into how wet stress can become very challenging to rainfed farming systems of susceptible cereal crops as heavy rain events may likely increase in frequency and amplitude (Taylor *et al* 2017, Salack *et al* 2018).

5. Conclusions

During the 2017 and 2018 rainy seasons, we investigated the effects of flooding and water stagnation on *Obatanpa* maize cultivars under ambient field conditions. The trials took place on a farm, but conditions were created to increase soil flooding, and water stagnation by over-irrigation and artificial reduction of runoff and the sub-surface drainage. Soil water fluctuations, the water stagnation depths (i.e., 2–3 cm and 7–8 cm), and the flooding durations (i.e., three days and six days) were monitored at different periods of growth and development stages of the crop. The results showed that these compound events reduce plant height, leaf expansion and delay the flowering phase. Temporary flooding at tasseling and six-leaf stages reduced aboveground biomass and grain production. Grain yield loss increases exponentially with an increased number of wet stress days, making the stress-day index (SDI) a valuable proxy to monitor and predict failure in maize production due to excess-water stress.

It is worth mentioning that various other challenges were encountered and addressed by applying some technical itineraries of this study. For example, some plots were attacked by fall-army worms (*Spodoptera frugiperda*) at the juvenile stage in both the 2017 and 2018 rainy seasons. Different types of pesticides were applied to control the pest. On the other hand, to minimize the effect of micronutrient deficiency induced by leaching, we used the recommended dose of chemical fertilizers such as N—P—K 20—10–10, urea, and ammonium sulfate at different dates by micro-dosing technique. All these challenges did not significantly influence the result of the experiments.

Hence, this unique case study demonstrates the potential loss and damages to maize production in the context of extreme rainfall and flooding in the Sahel region. Our results bring more insight into how wet stress can become very challenging to rainfed farming systems of susceptible cereal crops. Results of this unique case study demonstrate the potential loss and damages to maize production in the context of extreme precipitation and flooding in this region. Our results also highlight the need for well-fitted adaptation options such as plant breeding for more waterlogging tolerance, sustainable water management at field and basin levels, and crop insurance need to be adopted to care for and alleviate loss and damages caused by soil waterlogging flooding, and water stagnation under intense precipitation. Such cropland management options will help this region adapt to the current and anticipated climate change and climate extremes.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflict of Interest

The authors have no conflict of interests that can influence the work reported in this paper.

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