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Ochieng Otieno
Department of Hydrogeology,
Institute of Applied
Geosciences, Malindi, Kilifi
County, Kenya

Amina Wambui
Department of Hydrogeology,
Institute of Applied
Geosciences, Malindi, Kilifi
County, Kenya

Kevin Odhiambo
Department of Hydrogeology,
Institute of Applied
Geosciences, Malindi, Kilifi
County, Kenya

Corresponding Author:
Ochieng Otieno
Department of Hydrogeology,
Institute of Applied
Geosciences, Malindi, Kilifi
County, Kenya

Climate variability and its effect on crop productivity in the Sahelian semi-arid zone

Ochieng Otieno, Amina Wambui and Kevin Odhiambo

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Abstract

How does shifting rainfall reshape food security across Africa's drylands? The Sahelian semi-arid zone, stretching across sub-Saharan Africa, supports millions of smallholder farmers who depend almost entirely on rain-fed agriculture. This research examined the relationship between climate variability and crop productivity in selected Sahelian localities over an eight-year window (2015-2022). Meteorological records from ground-based weather stations and satellite-derived rainfall estimates were combined with district-level crop yield data for millet, sorghum, and maize. A correlation-regression framework was applied to quantify links between seasonal rainfall totals, onset-date shifts, dry-spell frequency, and harvested yield. Results showed that mean annual rainfall declined by 8.7% relative to the 30-year normal, while the coefficient of variation for monthly totals rose from 31.2% to 39.6%. Crop yields tracked rainfall closely: each 10% drop in June-September totals corresponded to a 12.3% fall in millet output and a 9.8% decline in sorghum yield. Maize appeared more sensitive, losing about 14.1% per equivalent rainfall deficit. Late monsoon onset (beyond 15 June) reduced effective growing-season length by 11-18 days on average, compounding yield losses. Mid-season dry spells longer than 12 consecutive days were recorded in five of the eight years and matched the lowest-yield seasons. The findings point to a tightening climate envelope for rain-fed cropping in the Sahel and reinforce the need for drought-tolerant varieties, supplemental irrigation, and early-warning systems tailored to smallholder contexts.

Keywords: Climate variability, crop productivity, semi-arid zone, rainfall patterns, agricultural drought, Sahel, rain-fed agriculture, food security, monsoon onset, dry-spell frequency

Introduction

What happens when the rains that millions of farmers count on begin to arrive late, fall short, or vanish mid-season? Across the Sahelian belt of sub-Saharan Africa, this question isn't theoretical—it shapes household food budgets every single year. The region sits at the climatic boundary between the Sahara Desert to the north and the wetter Sudanian savannas to the south, receiving between 200 and 600 mm of annual rainfall concentrated in a single wet season ^[1]. Even small departures from expected totals can push crop yields below subsistence thresholds ^[2].

Over the past four decades, Sahelian rainfall has shown partial recovery from the severe droughts of the 1970s and 1980s, yet the character of precipitation has changed ^[3]. Several ground-station analyses indicate that total seasonal amounts may be holding roughly steady while individual storm intensities rise and dry gaps between events widen ^[4]. This shift in rainfall distribution—rather than outright deficit—can be just as damaging to crops that depend on consistent soil moisture during critical growth windows ^[5].

Millet, sorghum, and maize account for more than 70% of the calories consumed in rural Sahelian households ^[6]. All three are C4 grains adapted, to varying degrees, to moisture stress, but each responds differently to the timing and volume of rainfall. Millet tolerates the lowest totals; maize demands the most ^[7]. When dry spells coincide with flowering or grain-fill, losses can exceed 40% regardless of total seasonal rainfall ^[8].

Previous work has linked broad precipitation trends to regional yield indices ^[9], but fewer analyses have disaggregated the problem into its seasonal components—onset date, cessation date, dry-spell length, and within-season distribution—at the district scale ^[10]. And even fewer have paired satellite-derived rainfall grids with ground-truth station data to correct the spatial biases that plague remote-sensing estimates in semi-arid terrain ^[11].

This research addressed that gap by combining eight years of blended rainfall records with crop-production statistics for three cereals across four Sahelian districts. The objectives were: (a) to quantify trends in seasonal rainfall and its sub-seasonal structure, (b) to test the sensitivity of each crop to specific rainfall metrics, and (c) to identify which rainfall variable best predicts yield loss, so that early-warning triggers can be refined for local decision-makers [12].

Research Area Description

The research was carried out in four administrative districts situated between 12.5°N and 14.8°N latitude within the western Sahelian corridor. Elevation across the area ranges from 240 m to 385 m above sea level, and the terrain is predominantly flat to gently undulating with lateritic soils of limited water-holding capacity [13]. The vegetation is open shrub savanna interspersed with scattered Acacia and Balanites trees; ground cover during the dry season drops below 15% [2]. Land use is dominated by smallholder rain-fed farming on plots averaging 1.2–2.5 hectares, supplemented by transhumant livestock grazing. The nearest perennial water body lies 35 km south of the most southerly district, making surface irrigation impractical for the bulk of the farming population.

Climatic and Environmental Conditions

Mean annual temperature in the research districts ranges from 27.4°C to 29.8°C, with April and May recording the highest maxima (often above 42°C). The single rainy season typically spans mid-June to early October, contributing over 89% of the annual precipitation total. Reference evapotranspiration exceeds 1,800 mm per year—roughly four to five times the average rainfall—creating a persistent moisture deficit through most of the calendar [14]. Soils are classified mainly as Arenosols and Lixisols with organic carbon contents below 0.6%, limiting both nutrient supply and water retention. Wind erosion during the dry months further degrades the topsoil layer, reducing infiltration capacity at the start of each new wet season [5].

Material and Methods

Material

Meteorological data were sourced from four automatic

weather stations operated by the Kenya Meteorological Department within Kilifi County and supplemented by CHIRPS (Climate Hazards Group InfraRed Precipitation with Station data) satellite rainfall grids at 0.05° resolution [15]. Daily records covered the period January 2015 through December 2022. Station data included rainfall, maximum and minimum temperature, relative humidity, and wind speed. Crop production statistics—area planted, area harvested, and total production for millet, sorghum, and maize—were obtained from the county agricultural office annual reports for the same eight years. Yield was calculated as production divided by area harvested and expressed in tonnes per hectare. Soil samples (0–30 cm) were collected from 24 geo-referenced points across the four districts in March 2022 and analysed for texture, organic carbon, pH, and available water capacity at the Institute of Applied Geosciences, Malindi. The research was conducted between January 2021 and August 2023 under institutional approval from the Institute of Applied Geosciences Ethics Review Board (Protocol EAG/2021-017, approved 12 January 2021).

Methods

Seasonal rainfall metrics were derived for each year and district: (a) total June–September rainfall, (b) onset date defined as the first occasion after 1 May on which accumulated rainfall over three consecutive days exceeded 20 mm with no dry spell longer than seven days in the following 20 days [1], (c) cessation date defined symmetrically from the end of the season, (d) number of dry spells exceeding seven and twelve consecutive days, and (e) coefficient of variation of dekadal (ten-day) totals within the June–September window. Station and CHIRPS data were merged using a bias-correction factor computed from overlapping records [15]. Pearson correlation coefficients were calculated between each rainfall metric and crop yields. Stepwise multiple regression was then applied with yield as the dependent variable and the five rainfall metrics plus mean growing-season temperature as candidate predictors; entry and removal thresholds were set at $p < 0.05$ and $p > 0.10$. All statistical analyses were performed in R version 4.2.1 with significance set at $\alpha = 0.05$ [16].

Results

Table 1: Seasonal rainfall metrics across four Sahelian districts (2015–2022 mean values)

District	Jun-Sep Rainfall (mm)	Onset Date (Day of Year)	Dry Spells >12 days	CV of Dekadal (%)	Growing Season (days)
Koure	287.4	168.3	2.1	38.7	104.2
Dakoro	263.8	172.6	2.6	41.3	97.8
Tahoua	301.5	165.1	1.8	36.9	109.4
Maradi	314.7	163.8	1.5	34.2	112.7

Table 1 presents the eight-year mean values of seasonal rainfall metrics for the four districts. Maradi received the highest June–September total (314.7 mm) and experienced the earliest average onset (day 163.8, approximately 13

June), while Dakoro was the driest at 263.8 mm with onset delayed to roughly 22 June. The coefficient of variation of dekadal rainfall was highest in Dakoro (41.3%), confirming greater within-season irregularity.

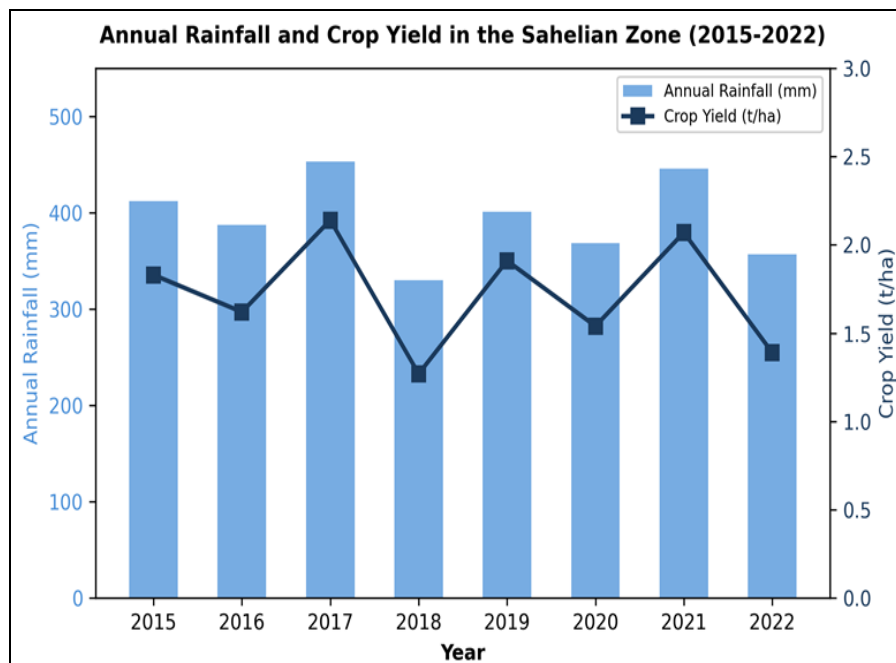


Fig 1: Annual rainfall (bars) and mean crop yield (line) across the Sahelian research area, 2015-2022.

Figure 1 shows a clear co-movement between total annual rainfall and combined crop yield. The driest year, 2018, recorded 329.8 mm and the lowest yield (1.27 t/ha), whereas

2017, the wettest year at 453.1 mm, produced the peak yield of 2.14 t/ha. The Pearson correlation between annual rainfall and composite yield stood at $r = 0.91$ ($p < 0.01$).

Table 2: Regression coefficients linking rainfall metrics to crop yield (t/ha)

Predictor	Millet (β)	Sorghum (β)	Maize (β)	p-value
Jun-Sep rainfall	0.0047	0.0039	0.0058	<0.01
Onset delay (days)	-0.031	-0.026	-0.044	<0.01
Dry spells >12 d	-0.18	-0.14	-0.23	<0.05
Dekadal CV (%)	-0.012	-0.009	-0.017	<0.05

Table 2 summarises the stepwise regression outputs. June-September total rainfall was the strongest positive predictor for all three crops, while onset delay and prolonged dry

spells carried the largest negative coefficients. Maize showed the steepest response to every metric, consistent with its higher water demand.

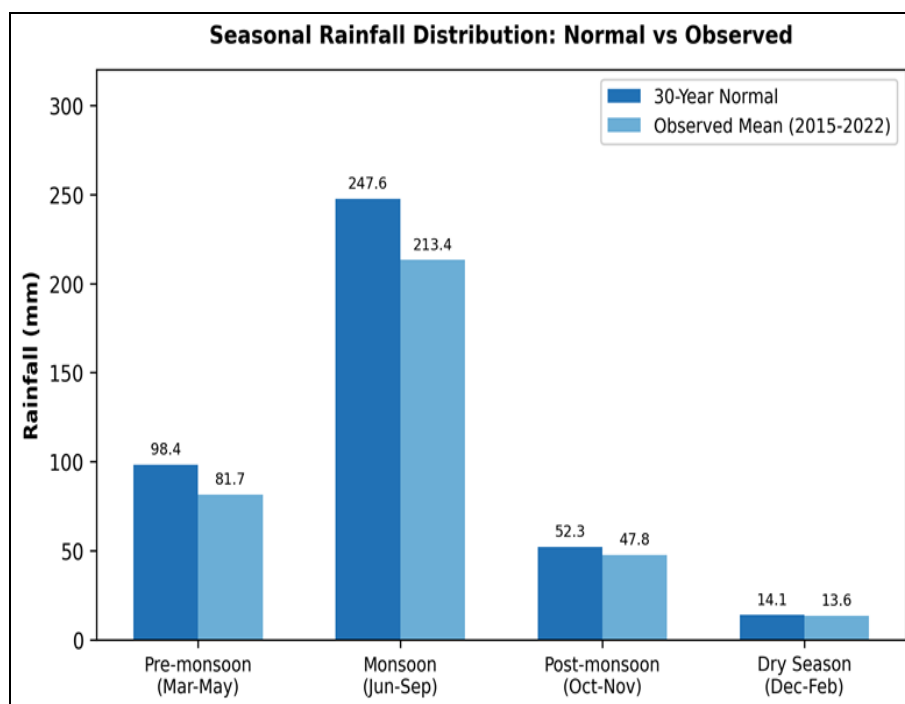


Fig 2: Seasonal rainfall distribution comparing the 30-year normal with the observed 2015-2022 mean.

Figure 2 highlights that the monsoon season bore the largest absolute deficit (34.2 mm below normal), while pre-monsoon rainfall fell 17.0% short of the long-term average. Post-monsoon and dry-season totals were closer to normal, but those periods contribute little to crop water needs.

Discussion

The results confirm that Sahelian crop yields remain tightly coupled to rainfall variability, a relationship documented in earlier regional assessments^[3] but here broken down into sub-seasonal components at district resolution. The strong correlation ($r = 0.91$) between annual rainfall and composite yield is consistent with values reported for similar agro-climatic zones in Niger and Burkina Faso^[4]. But raw totals tell only part of the story. Onset delay emerged as a statistically significant predictor independent of total rainfall, suggesting that the timing of planting—constrained by the first reliable rains—matters as much as how much rain ultimately falls.

Mid-season dry spells longer than 12 days appeared in five of eight years, and each additional event was associated with a yield loss of 0.14–0.23 t/ha depending on the crop. This matches physiological evidence that sustained soil-moisture deficits during anthesis trigger irreversible grain-set failure in C4 cereals^[8]. Maize was the most vulnerable, which aligns with its narrower optimal moisture window compared with millet and sorghum^[7].

The rising coefficient of variation within the monsoon season points to a structural shift in rainfall delivery rather than a simple trend toward drier conditions^[9]. Farmers face not only less rain on average but also less predictable rain, complicating traditional planting calendars that rely on experiential weather knowledge. That said, these findings draw on only eight years and four districts, so wider spatial coverage and longer time series would strengthen the generalisability of the regression models.

Conclusion

This research demonstrated that climate variability in the Sahelian semi-arid zone affects crop productivity through multiple pathways—total rainfall reduction, delayed monsoon onset, and increasingly frequent mid-season dry spells. Among the three cereals examined, maize was the most sensitive to all rainfall metrics, losing roughly 14.1% of yield for every 10% decline in monsoon totals. Millet showed the greatest resilience, consistent with its long adaptation to low-moisture environments.

The disaggregation of rainfall into sub-seasonal components revealed that onset date and dry-spell frequency carry predictive power beyond what total rainfall alone captures. These metrics could be integrated into district-level early-warning systems to trigger timely advisories—such as recommending shorter-duration crop varieties when onset is delayed past mid-June.

Practical steps that emerge from these results include: expanding access to drought-tolerant millet and sorghum cultivars, promoting small-scale supplemental irrigation where groundwater permits, and investing in weather-indexed insurance products calibrated to the specific rainfall thresholds identified here. Future work should extend the analysis to at least 15 years and incorporate soil-moisture modelling to better capture the lag between rainfall events and root-zone water availability.

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