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Intra-seasonal rainfall patterns and extremes drive maize productivity and nitrogen use in sub-humid Zimbabwe

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ABSTRACT

Background and purpose: Increasing intra-seasonal rainfall variability poses a major challenge to the sustainable intensification of rainfed maize systems in sub-Saharan Africa. This study investigates how intra-seasonal rainfall patterns and extreme dry and wet events affect maize productivity and nitrogen (N) use, particularly under crop residue mulching—a practice widely promoted to improve soil water and N availability.
Methods: A maize field experiment with manipulated rainfall conditions was conducted over two cropping seasons (2022–23 and 2023–24) in sub-humid Zimbabwe. The factorial design combined three rainfall treatments (ambient, 30 % reduced rainfall, and heavy rainfall with two additional artificial events of 100 mm day^{-1} each), with or without mulch (0 vs. 6 t DM ha^{-1}) and N fertilization (0 vs. 80 kg N ha^{-1}). Measured variables included aboveground biomass, plant N accumulation, grain yield, yield components, and harvest indices. The relative influence of rainfall variability and management practices was assessed.
Results: The two seasons showed contrasting rainfall: 2022–23 was near-normal, while 2023–24 (an El Niño year) was drier, with uneven rainfall distribution. Intra-seasonal rainfall patterns and extremes explained 78 % of maize yield variability. Poor rainfall distribution significantly decreased maize productivity and N use, despite adequate total seasonal rainfall. Rainfall reduction decreased yield by 22 % in 2022–23 but increased it by 20 % in 2023–24. Heavy rainfall, especially with N fertilization, doubled grain yield in 2023–24. Mulching provided no buffering effect and reduced maize biomass and N uptake by about one-third in 2023–24.
Conclusions: Intra-seasonal rainfall patterns and extremes were the dominant factors affecting maize productivity and N use, far outweighing the effects of mulch and N fertilization. These findings highlight the need for cropping strategies that better account for intra-seasonal rainfall variability to improve the resilience and sustainability of rainfed maize systems in sub-Saharan Africa.

1. Introduction

Climate variability is a major driver of crop yield fluctuations, with much of this variability attributed to changes in rainfall patterns—particularly changes in their distribution over time—that are intensifying with global warming (IPCC, 2021; Rohde, 2023). The

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frequency of extreme events (*i.e.,* droughts and heavy rains) is likely to double with each additional degree of warming, especially in tropical regions (Myhre et al., 2019). These trends are particularly alarming in sub-Saharan Africa (IPCC, 2022), with considerable implications for food security (Van Ittersum et al., 2016), given that population growth and food demand are projected to more than double by 2050.

Maize (*Zea mays* L.) is the most important staple crop in sub-Saharan Africa (*e.g.,* Shiferaw et al., 2011), predominantly cultivated by smallholder farmers under rainfed conditions, with low average yields (*e.g.,* Cairns et al., 2021). Yield anomalies in these systems can be highly correlated with interannual rainfall variability, strongly influenced by the El Niño–Southern Oscillation (ENSO) (Cane et al., 1994). In Zimbabwe, El Niño phases often bring prolonged mid-season dry spells, whereas La Niña phases are associated with wetter conditions and more erratic, heavier rains (Mpheshea et al., 2025). However, Phillips et al. (1998) emphasized that seasonal ENSO classifications overlook critical intra-seasonal rainfall dynamics. Regardless of total seasonal rainfall, an uneven intra-seasonal rainfall distribution that poorly aligns with crop water requirements can profoundly alter maize performance (Vogel et al., 2019). However, the impacts of rainfall extremes and their timing within specific crop growth stages remain poorly understood (Zaitchik et al., 2023). Few studies have examined maize sensitivity to changes in intra-seasonal rainfall patterns and extremes in sub-Saharan Africa using agroclimatic indices and statistical modelling (*e.g.,* Chemura et al., 2022; Hoffman et al., 2018; Marcos-Garcia et al., 2024) or crop simulation models (Waha et al., 2013). While these studies provide useful information, they often lack empirical validation under real field conditions. *In-situ* rainfall manipulation experiments provide a valuable tool to assess how cropping systems respond to altered rainfall regimes compared to a control (Yahdjian and Sala, 2002). Such field observations are key for establishing causal relationships between rainfall variation and crop performance (Hu et al., 2024).

Low maize productivity in sub-Saharan Africa, including Zimbabwe, is also attributed to inherently poor soil fertility and decades of continuous cropping with limited nutrient inputs (Sanchez, 2002). Nitrogen (N) is the most limiting nutrient in these low-fertility soils, with average mineral N fertilizer application rates as low as 14 kg N ha^{-1} yr^{-1} (Vanlauwe et al., 2023). Even in more fertile soils, ongoing nutrient export through harvested biomass leads to gradual soil mining (Sánchez, 2010). However, while increasing mineral N use is essential for improving crop productivity (Falconnier et al., 2023a), its adoption is often constrained by high fertilizer prices and low perceived profitability (Tittonell and Giller, 2013). In this context, combining mineral N fertilizer with other soil management practices offers a promising pathway to boost productivity and improve soil fertility (Cardinael et al., 2022). One such practice is crop residue mulching, which helps maintain soil moisture and reduce nutrient losses from erosion and runoff (Thierfelder and Wall, 2009), contributing to long-term soil fertility through carbon (C) inputs (Shumba et al., 2024) and nutrient cycling (Vanlauwe et al., 2010). Nevertheless, the effect of mulching on N availability to crops remains uncertain, as microbial N immobilization can limit crop N uptake, depending on several factors such as the residue quality (C:N ratio) (Chaves et al., 2021; Gentile et al., 2008). Furthermore, the adoption of mulching is hindered by labour requirements, competing uses for livestock feed and insufficient biomass production (Baudron et al., 2014). Given the scarcity of both N fertilizers and crop residues, their efficient use is critical. Yet, little is known about the effectiveness and potential interactions of these inputs under conditions of rainfall extremes. Addressing this knowledge gap is key for understanding maize yield response and developing effective, local adaptation strategies for climate resilience.

This study aimed to provide insights on how intra-seasonal rainfall patterns and extremes—namely droughts or heavy rainfall events—affect maize productivity and N use through a rainfall manipulation experiment. Conducted over two cropping seasons under field conditions in sub-humid Zimbabwe, the study analysed different rainfall treatments and identified key extreme wet and dry events driving aboveground biomass and grain yield of maize. It also examined the relative contribution of mulch and N fertilizer to maize performance. We hypothesized that (i) intra-seasonal rainfall patterns and the timing of extreme events regarding crop growth stages are key determinants of maize response, (ii) both reduced and heavy rainfall events decrease maize productivity and N uptake; and (iii) mulch buffers the adverse effects of rainfall extremes on maize biomass accumulation and N uptake.

2. Materials and methods

2.1. Study site

The study was conducted at the experimental station of the Agro-Industrial Park of the University of Zimbabwe, located 13 km north of Harare (17°42'13.5"S, 31°00'29.4"E, altitude 1495 m). The field experiment was established in 2022 as part of a new long-term trial (https://glten.org/experiments/368). Here, results from the first two maize cropping seasons, 2022–23 and 2023–24, are presented. Before the experiment, the site had been under sugar bean (*Phaseolus vulgaris* L.) cultivation for two years. The soil at the site is classified as a *Rhodic Ferralsol* (IUSS Working Group WRB). The initial soil characterization, conducted in November 2022 (Table 1), revealed a homogeneous loam texture (USDA Soil Taxonomy) across the 0–100 cm profile, with a dominant silt content > 410 g kg^{-1} soil. In the 0–20 cm layer, clay and sand contents were 239 and 335 g kg^{-1} soil, respectively. Soil organic carbon and total N concentrations in this layer were 13.5 g C kg^{-1} and 1.13 g N kg^{-1} soil, respectively. Soil pH-water was 6.9 and the cation exchange capacity was 14.1 $cmol_c$ kg^{-1} soil. Soil bulk density averaged 1.28 g cm^{-3}. Stone (> 2 mm) mass content showed a strong spatial variability and varied by depth, with an average of 18.5 % in the 0–20 cm layer. The average mineral N stock in the 0–50 cm layer prior to the start of the experiment was 66 kg N ha^{-1}.

The site is characterized by a subtropical climate with cool-dry winters and hot-wet summers, classified as Cwa according to the Köppen–Geiger classification (Kottek et al., 2006). The rainy season is unimodal and spans from November to April, with variable inter-seasonal totals and intra-seasonal distribution. Based on 13 years of historical data (2009–2022), the average annual rainfall at the site is 725 mm. Average cumulative rainfall during the maize growing season (*i.e.,* from mid-November to mid-May) is 680 mm. The historical average of minimum and maximum air temperatures during the maize growing season are 16.4 °C and 26 °C, respectively.

2.2. Experimental design

2.2.1. Factorial treatments

The experiment included three factors: rainfall, mulch application, and N fertilization. The rainfall factor consisted of three main treatments: (i) ambient rainfall of the season; (ii) reduced rainfall, with a permanent reduction of 30 % of ambient rainfall; and (iii) heavy rainfall, which refers to ambient rainfall plus two additional extreme events of 100 mm day^{-1} each per season. The reduced rainfall treatment was implemented using a rainfall exclusion system (Fig. S1), designed to minimize microclimate effects. Transparent polycarbonate rainout shelters were placed on a wooden frame above the maize canopy. Each shelter had an effective width of 14 cm and was installed at an equidistance of 50 cm, covering 30 % of the plot surface. The structure stood 2.5 m high on the southern side and 3 m on the northern side to ensure maximum homogeneity in solar radiation incidence. Rainfall water intercepted by the shelters was collected via gutters and downpipes and diverted away from the plots using a drainpipe. The heavy rainfall treatment was implemented using an irrigation system with borehole water. The chosen amount of 100 mm per event corresponds to the site's historical maximum daily rainfall (104 mm). The timing of these

Table 1
Initial soil characteristics of the study site. Values represent the mean of the three block replicates ± standard error (SE).

Depth (cm)	Clay content (g kg^{-1} soil)	Silt content (g kg^{-1} soil)	Sand content (g kg^{-1} soil)	Texture class	pH-water	CEC (cmol$_c$ kg^{-1})	SOC (g C kg^{-1} soil)	Total N (g N kg^{-1} soil)	Bulk density (g cm^{-3})	Mass of coarse fraction (%)
0–10	235 ± 14	410 ± 9	355 ± 15	Loam	6.8 ± 0.1	15.1 ± 1.4	14.5 ± 1.5	1.26 ± 0.15	1.25 ± 0.04	17.5 ± 0.9
10–20	242 ± 17	443 ± 12	315 ± 18	Loam	6.9 ± 0.1	12.8 ± 1.3	12.5 ± 0.7	1.02 ± 0.07	1.30 ± 0.02	19.5 ± 1.1
20–30	247 ± 15	432 ± 8	321 ± 15	Loam	7.0 ± 0.1	14.1 ± 1.9	10.3 ± 0.6	0.82 ± 0.06	1.25 ± 0.01	23.9 ± 1.5
30–50	261 ± 16	425 ± 8	314 ± 16	Loam	6.6 ± 0.1	12.1 ± 1.3	7.4 ± 1.0	0.60 ± 0.10	1.27 ± 0.06	38.2 ± 0.9
50–75	253 ± 17	431 ± 11	316 ± 19	Loam	6.1 ± 0.1	10.3 ± 1.1	5.4 ± 1.1	0.48 ± 0.11	1.26 ± 0.03	34.0 ± 8.0
75–100	234 ± 16	423 ± 16	342 ± 18	Loam	6.2 ± 0.1	8.7 ± 1.0	4.7 ± 0.8	0.46 ± 0.08	1.21 ± 0.03	32.0 ± 5.0

artificial rainfall events varied between seasons to explore the effect of their occurrence regarding maize growth stages and N fertilizer application.

The mulch factor consisted of two levels: no mulch (M0) and mulch added at a rate of 6 t dry matter (DM) ha^{-1} yr^{-1} (M6). Intact maize stover collected from the previous cropping season was applied on the soil surface shortly after sowing (Table S1). In 2022–23, mulch was sourced from other plots, while in 2023–24, residues produced within each plot were reused. The average C:N ratios of the applied residues were 57.4 and 69.4 in the respective seasons.

The N fertilization factor comprised two levels: no fertilization (N0) and 80 kg N ha^{-1} yr^{-1} (N80). The fertilization was split into three applications, 20 kg N ha^{-1} at sowing, 30 kg N ha^{-1} at the six-leaf stage (first top dressing) and another 30 kg N ha^{-1} at the ten-leaf stage (second top dressing). Ammonium nitrate was used as the N source and placed within 12.5 cm distance from maize rows. Top dressing dates were closely aligned between 2022–23 and 2023–24 (Table S1). The N80 rate represents a compromise between typical smallholder application rates (about 14 kg N ha^{-1} yr^{-1} on average) and commercial rates (about 160 kg N ha^{-1} yr^{-1}). The split applications and row placements reflect common local practices in the region.

For comparison purposes, an additional non-replicated, mulch-free treatment was set up to better characterize maize yield under potential growth conditions (hereafter referred to as yield potential). For this treatment, the plot received as needed, two applications of 35 mm each in 2022–23, and three of 26 mm, 25 mm and 38 mm in 2023–24 (Table S1). Ammonium nitrate quantities were doubled at each split application resulting in a rate of 160 kg N ha^{-1} yr^{-1}.

2.2.2. *Experimental layout*

The factorial experiment was set up as a split-plot within a randomized complete block design with three replicates (Fig. 1). The rainfall treatments were assigned to the main plots, while mulch and N fertilization levels were combined in the subplots, resulting in a total of 36 plots plus the one for yield potential. Plot size was 9 m × 7 m (63 m^2). Block replicates and main plots were separated by 4 m wide grass strips to prevent lateral water transfer between rainfall treatments. Additionally, subplots within the same rainfall treatments were separated by 2 m wide grass strips. Treatments were maintained on the same plots in the second cropping season (no rotation).

2.2.3. *Crop management*

A medium maturity, drought tolerant maize variety, PGS 63—widely cultivated in Zimbabwe—was used (Chikobvu et al., 2014). Sowing followed local minimum-tillage practices. Planting stations of approximately 15 cm in diameter and 10 cm deep were prepared using a hand hoe shortly before sowing. Inter-row and an in-row spacings of 90 cm and 25 cm, respectively, were used, targeting a plant density of 44 444 plants ha^{-1}. Two seeds were planted per station, with thinning and gap filling carried out soon after emergence. Basal phosphorus (P) and potassium (K) were applied in all plots at sowing, placed within the planting station, but avoiding direct seed contact, ensuring P and K were non-limiting. Single super phosphate and muriate of potash were applied at 15 kg P ha^{-1} yr^{-1} and 30 kg K ha^{-1} yr^{-1}, respectively. For pest control, localized application of granular Ecoterex 0.5 GR was used as needed to treat plants with fall armyworm (*Spodoptera frugiperda*) infestation. A chemical weed treatment was applied prior to sowing only

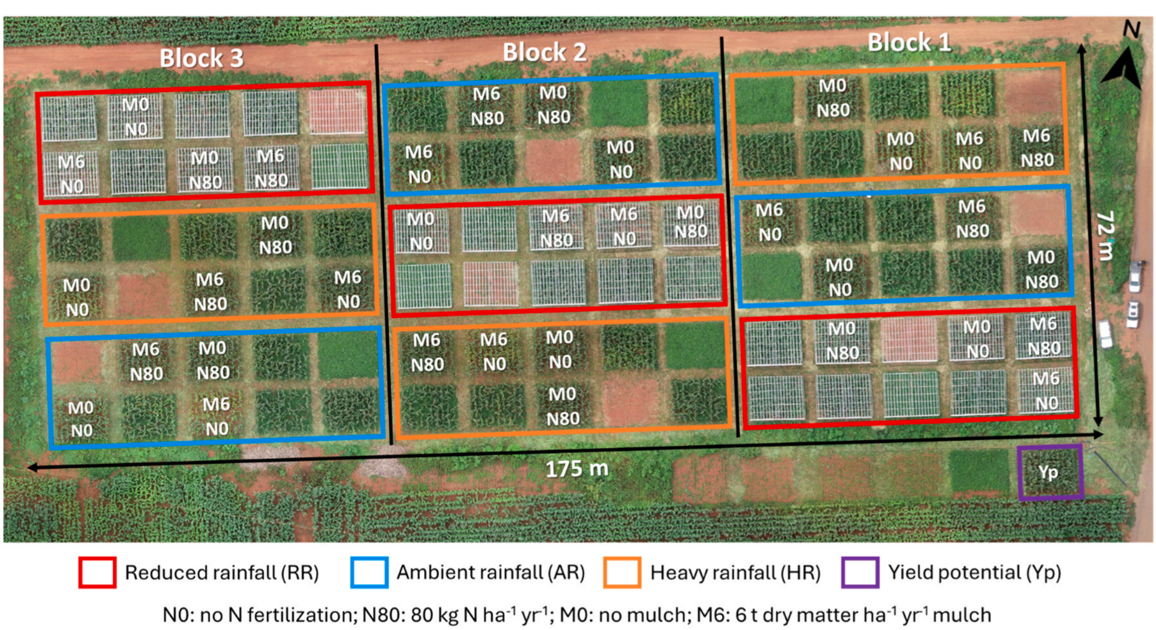

Fig. 1. Aerial view of the experimental site (February 2023). Photo credit: CIRAD.

in 2022 by spraying glyphosate 480 SL at a rate of 2 kg active ingredient ha^{-1} (as *Isopropylamine* salt). Between sowing and flowering stage, weeds were uniformly controlled in all treatments by manual hoe weeding every two weeks.

2.3. Plant sampling and analyses

Plant sampling was conducted within net plots (48 m^2) by leaving a 1 m border on all sides of each plot. At the six-leaf, ten-leaf (preceding 1st and 2nd N top dressings, respectively) and at flowering stages, four representative plants were sampled from one half of each net plot. The remaining half (~15.3 m^2 area) was harvested at physiological maturity. Fresh weight of ears and stover, along with plant and ear counts, were recorded in the field. A subsample of four representative plants was then collected. At the six- and ten-leaf stages, entire plants were considered. At flowering, they were partitioned into leaves + stem and ears, while at harvest, they were divided into leaves, stem, cobs, and grains. Samples were oven-dried at 60 °C until constant weight was reached, after which the dry weight of each plant component was determined. Grains were counted for yield components determination and final yield was adjusted to 12.5 % moisture content. For N content, a subsample of each plant component was ground and analysed separately using a C/N elemental analyzer (EuroEA3000, EuroVector S.p.A., Italy). Total aboveground biomass and N accumulation were calculated by weighting the total N concentrations of the individual plant components according to their biomass proportions.

2.4. Statistical analysis

Statistical analyses were performed using R software, version 4.4.2 (R Core Team, 2021). The main effects of the factors and their interactions were assessed using analysis of variance (ANOVA). Since rainfall treatments are primarily determined by year, the two cropping seasons were analysed separately. Rainfall was treated as a categorical factor (*i.e.,* ambient, reduced, and heavy rainfall) to capture its overall effect. Following the experimental design, a linear mixed model was fitted with rainfall, mulch, and N fertilization as fixed effects using the '*lmer*' function from the '*lme4*' package (Bates et al., 2015). Block replicates were included as a random effect, and a nested random effect for rainfall main plots within replicates was included in the model when it explained significant variance. Prior to ANOVA, model residuals were statistically checked for normality (Shapiro–Wilk test) and homoscedasticity (Breusch–Pagan test) and visually inspected (diagnostic plots) using the '*performance*' package functions (Kozak and Piepho, 2018). The significance of the effects was assessed using the '*Anova*' function from the '*car*' package. When significant effects were detected by ANOVA, means were compared based on Tukey's test at 5 % significance level using the '*emmeans*' function from the '*emmeans*' package (Lenth et al., 2018).

2.5. Rainfall pattern and extremes analysis

2.5.1. Selection and calculation of indices

Rainfall indices were used to better describe intra-seasonal rainfall dynamics and to compare rainfall treatments over the two cropping seasons. Guided by an exploratory analysis presented in Supplementary Section S1, ten indices listed by the World Meteorological Organization Expert Team on Sector-specific Climate Indices (WMO ET-SCI) were initially selected to cover the intensity, duration, and frequency of dry and wet extremes. Among the selected indices, the Standardized Precipitation Index (SPI)—which is a statistical measure of precipitation anomalies in a given location (McKee et al., 1993) and widely used in agricultural studies to characterize short-term droughts (Zhang et al., 2023)—was employed in this study as an overall index to assess dry and wet patterns. Additionally, given the occurrence of heavy rainfall events and the applied irrigation in the yield potential treatment around flowering, total precipitation within a 21-day window centred on this critical stage (Prec_R1) was calculated (Lobell et al., 2011). The percentile-based indices and SPI were calculated based on historical site data from 2009 to 2022. Moreover, as maximum temperatures were particularly high during the second cropping season, an index of maximum temperature intensity (EHD_I30) derived from Becker et al. (2025), was calculated. The 30 °C threshold used represents an average value of the 95th and 99th percentiles over the historical data (2009–2022). While most of the indices were calculated for the whole growing season, the maximum consecutive dry days (CDD) and SPI were calculated as crop growth phase–specific. The maize growth cycle was divided into five phases with common dates across both cropping seasons, as detailed in Table S2. To limit the number of variables, only critical phases between the six-leaf stage and physiological maturity were considered.

2.5.2. Random forest analysis and dependence partial plots

To determine the most important explanatory variables driving total aboveground biomass and grain yield under the different rainfall treatments over the two cropping seasons, a random forest analysis was employed. Random forest is a non-parametric machine learning method able to address nonlinear and hierarchical relationships (Breiman, 2001) and has been used in several recent studies to investigate the impact of climate extremes on crop performance (*e.g.,* Feng et al., 2018; Hoffman et al., 2018). To avoid collinearity between rainfall extreme indices, Pearson correlation coefficients (r values) were performed separately within each set of indices, first at the full growing season scale, then separately between the CDD and SPI indices within each crop growth phase. Variable filtering (Supplementary Section S2) was performed based on $|r| < 0.85$ (Zhu et al., 2024). The final set of retained indices for analysis after filtering is presented in Table 2. Random forest is also well suited for assessing complex interactions between biophysical and management factors (Jeong et al., 2016). Therefore, the mulch and N fertilization levels were included as explanatory variables in the model. The yield potential treatment was also included in the dataset. The random forest model was implemented using the '*randomForest*' package in R (Liaw and Wiener, 2002) with 1000 trees, and *mtry*, representing

Table 2
List of rainfall and temperature indices.

Index ID	Definition	Unit
Rx5day	Seasonal maximum consecutive 5-day rainfall	mm
Rnn99p	Seasonal count of days with precipitation > 99th percentile	day
PRCPTOT	Seasonal cumulative rainfall on wet days (precipitation ≥ 1 mm)	mm
Prec_R1	Total rainfall within 21-day period centred on flowering	mm
CDD_V6-V10	Maximum number of consecutive dry days (precipitation < 1 mm) of V6-V10 phase	days
SPI_V6-V10	Standardized precipitation index reflecting dry/wet conditions of V6-V10 phase	(-)
SPI_V10-R1	Standardized precipitation index reflecting dry/wet conditions of V10-R1 phase	(-)
SPI_R1-R6	Standardized precipitation index reflecting dry/wet conditions of R1-R6 phase	(-)
EHD_I30	Seasonal extreme hot days intensity as sum of degree days when $T_{max} > 30$ °C	°C day

the number of predictors sampled at each split, was set to 4. Results were averaged over 100 runs, and variable importance was assessed with the increase in mean squared error (MSE) metric. Cross-validation was not performed, as the model was used for only variable importance ranking. In addition, partial dependence plots were used to examine the influential magnitude and direction of explanatory variables.

3. Results

3.1. Weather and rainfall pattern characteristics

The two experimental seasons showed distinctly different weather conditions, with the mid- and late season of 2023–24 being extremely dry and hot. Despite cumulative ambient rainfall being close to the 2009–2022 reference period average (680 mm), with 727 mm in 2022–23 and 599 mm in 2023–24, the two seasons exhibited contrasting intra-seasonal distribution patterns (Fig. 2). Minimum temperature averaged 14.4 °C and 15.2 °C, while average maximum temperatures were 26.1 °C and 28.1 °C in 2022–23 and 2023–24, respectively. The 2023–24 El Niño season was characterized by particularly an early cessation of rainfall at the end of January, followed by high maximum temperatures from mid-February onwards. Between mid-February and mid-April, the average maximum temperature reached 29.4 °C, with values exceeding 30 °C on 26 days.

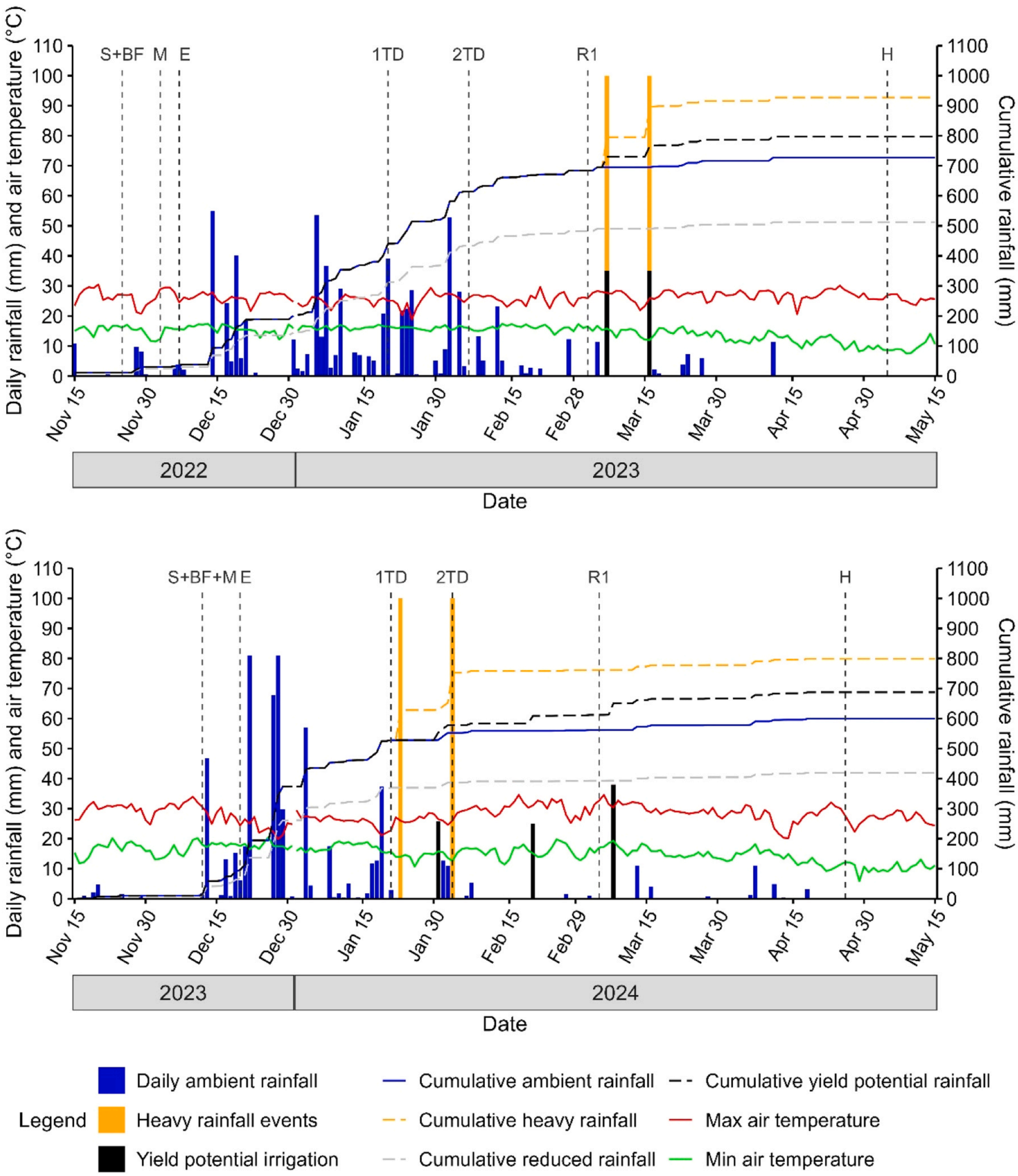

Fig. 2. Daily ambient rainfall, minimum and maximum air temperatures; simulated heavy rainfall events and irrigation rates applied to the yield potential treatment, along with cumulative rainfall recorded under the different rainfall treatments. Abbreviations for dated events: S+BF: sowing + basal fertilization, E: emergence, M: mulch application, 1TD: 1st N top dressing, 2TD: 2nd N top dressing, R1: flowering stage, H: harvest. Abbreviations for development phases: S-E: sowing to emergence, E-V6: emergence to six-leaf stage, V6-V10: six- to ten-leaf stage, V10-R1: ten-leaf stage to flowering, R1-R6: flowering to physiological maturity.

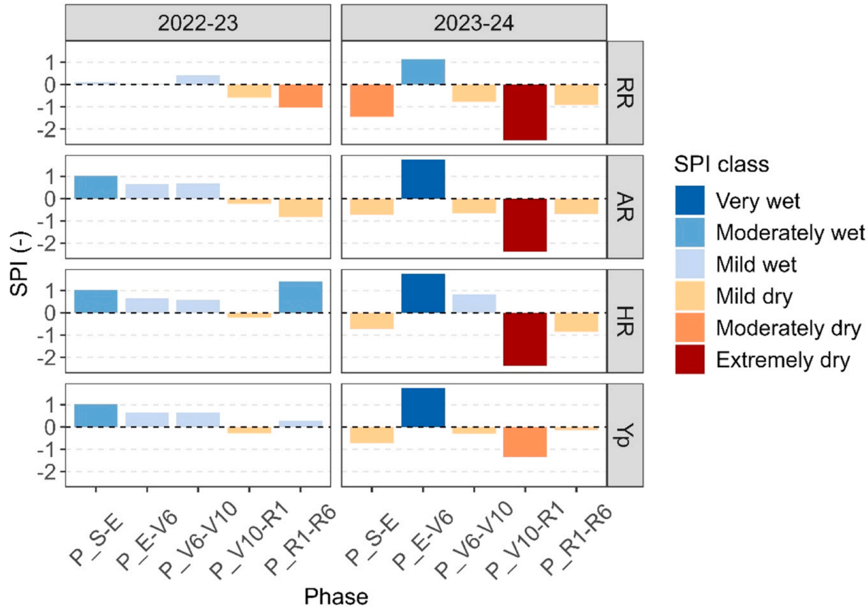

Fig. 3. Specific Standardized Precipitation Index (SPI) values and classes over the 2022–23 and 2023–2024 cropping seasons under rainfall treatments. RR: reduced rainfall, AR: ambient rainfall, HR: heavy rainfall, Yp: yield potential treatment, P_S-E: sowing to emergence phase, P_E-V6: emergence to six- leaf phase, P_V6-V10: six-leaf to ten-leaf phase, P_V10-R1: ten-leaf to flowering phase, P_R1-R6: flowering to physiological maturity phase.

Compared to the 2009–2022 reference period, the 2022–23 growing season exhibited a relatively balanced intra-seasonal rainfall distribution pattern (Fig. 3). The sowing to ten-leaf phase was, comparatively to the reference period, mildly-to-moderately wet under all rainfall treatments, with SPI values between 0.02–1.02, whereas the ten-leaf to flowering phase was mild dry. During the flowering to physiological maturity phase, mildly dry conditions persisted under the ambient and reduced rainfall treatments, whereas the application of heavy rainfall events and potential yield irrigations (Fig. 2) shifted SPI classes to moderately wet and mildly wet, respectively. Conversely, the 2023–24 season began with mildly to moderately dry conditions during the sowing to emergence phase. The emergence to six-leaf phase was moderately wet under reduced rainfall and very wet under the other rainfall treatments, with SPI reaching 1.75 (432 mm, equivalent to 72 % of total ambient seasonal rainfall). This was followed by a mildly dry six- to ten-leaf phase, except under the heavy rainfall treatment, where the two heavy rainfall events resulted in mildly wet conditions. The ten-leaf to flowering phase was extremely dry under all rainfall treatments, with the lowest recorded SPI value of −2.5 (total ambient rainfall of 8.4 mm), except for the yield potential treatment where conditions were reduced to moderately dry thanks to irrigation. The flowering to physiological maturity phase was mildly dry, though the SPI value was close to normal (−0.12) under the yield potential treatment.

3.2. Maize productivity and N use

3.2.1. Total aboveground biomass and N accumulation

Due to dry and hot conditions in 2023–24, total aboveground biomass and N accumulation were substantially lower than in the previous season. At harvest under ambient rainfall, total aboveground biomass and N accumulated were 11.8 t DM ha^{-1} and 116.6 kg N ha^{-1} in 2022–23 but dropped to 2.9 t DM ha^{-1} and 22.7 kg N ha^{-1} in 2023–24 (Table 3). Total aboveground biomass declined by about 1.4 t DM ha^{-1}, averaged across rainfall treatments, between flowering and harvest during the second season (Fig. S2). This decline corresponded to an average loss of 15.8 kg N ha^{-1} (Table 3 and Table S4). Rainfall treatment had no significant effect on total aboveground biomass and N accumulation at most growth stages during the two cropping seasons, except at flowering in 2022–23 when reduced rainfall decreased total aboveground biomass and N accumulation by 2.9 t DM ha^{-1} and 30 kg N ha^{-1}, respectively, compared to ambient rainfall (Table S4).

Mulch application had no significant effect in 2022–23, but in 2023–24 it significantly reduced total aboveground biomass at all growth stages (*i.e.,* at harvest: 4.1 t DM ha^{-1} in M0 vs. 2.7 in M6), with a more pronounced effect observed under ambient and heavy rainfall compared to reduced rainfall (Table 3, Table S4). As expected, N accumulation at harvest increased with N fertilizer addition during both cropping seasons, with average increases of 31.2 kg N ha^{-1} in 2023 and 11.8 in 2024 under N80 compared to N0 (Table 3). This corresponded to apparent N fertilizer recovery rates of 39 % and 15 %, respectively, which is low to very low.

Significant interactions between rainfall and mulch, as well as between rainfall and N fertilization, were observed only during the 2023–24 cropping season. Mulch application significantly decreased N accumulation in total aboveground biomass under ambient and heavy rainfall at harvest, while the decrease was relatively smaller under reduced rainfall (Fig. 4c). However, both total aboveground biomass and N accumulation were significantly affected by the rainfall and N fertilization interaction. Under heavy rainfall, N0 resulted in the lowest total aboveground biomass at harvest (2.81 t DM ha^{-1}) and in the lowest N accumulation (15.4 kg N ha^{-1}), whereas N80 showed the highest values (4.3 t DM ha^{-1} for total aboveground biomass and 40 kg N ha^{-1} for N accumulation) (Figs. 4a, 4b). A similar trend was observed at flowering (Fig. S3). No significant effects were found for the three-way rainfall × mulch × N fertilization interaction or for the two-way mulch × N fertilization interaction on total aboveground biomass and N accumulation at most growth stages in either cropping season.

3.2.2. Grain yield, yield components and harvest indices

As with total aboveground biomass, maize grain yield in the ambient rainfall treatment was significantly lower in the dry 2023–24 season compared to 2022–23 season (0.5 and 5.0 t ha^{-1}, respectively) (Table3). Rainfall treatment significantly affected grain yield and yield components in both cropping seasons. In 2023, reduced rainfall led to a 1.1 t ha^{-1} decrease (–22 %) in grain yield compared to ambient rainfall, associated with a lower number of ears per plant. In contrast, grain yield was notably higher in 2024 under reduced rainfall (+0.1 t ha^{-1} or +20 %) compared to ambient rainfall, with a higher number of grains per ear (Table S5). Mulch and N fertilization had no significant effects in 2023. In 2024, however, both factors significantly influenced grain yield and its components, through their main effects and interactions with rainfall treatments. Grain yield in 2024 was consistently lower with mulch application (M6) and higher with N fertilization (N80) (Table 3). These effects were most pronounced under heavy rainfall, where the N80 and M0 treatments achieved the highest grain yields, whereas N0 and M6 yields were like those of the other treatments (Figs. 4d, 4f). Thus, grain yield under heavy rainfall was on average twofold higher than under ambient rainfall, associated with a significantly higher number of grains per ear. Grain yield reduction in the mulch treatments was mainly linked with a decrease in the number of grains per ear compared to the treatments without mulch. Conversely, these yield components increased with N fertilization (+0.21 ears per plant and + 50 grains per ear) compared to the non-fertilized treatments (Table S5).

Dry matter harvest index and N harvest index declined in 2024 compared to 2023. The average dry matter harvest index was approximately halved (0.37 vs. 0.17), and the average N harvest index decreased from 0.55 to 0.34. Compared to ambient rainfall, reduced rainfall tended to decrease both indices in 2023 but had no effect on them in 2024. In contrast, heavy rainfall tended to increase both indices relative to ambient rainfall, though the effect was not statistically significant in 2024. Nitrogen fertilization (N80) also significantly increased both indices in 2024 as compared to no N fertilization (N0) (Table 3). This effect was observed across all rainfall treatments, with the most pronounced increase observed for the dry matter harvest index under heavy rainfall (Fig. 4e). On the other hand, both indices were not significantly affected by mulch application (Table 3). No significant effects were observed for the rainfall × mulch × N fertilization interaction and the mulch × N fertilization interaction on grain yield, yield components, or harvest indices.

3.3. *Factors affecting maize productivity*

3.3.1. *Relative importance of explanatory variables*

The random forest analysis, assessing the relative importance of rainfall extremes, maximum temperature indices, mulch, and N fertilization, explained 84 % of the variation in total aboveground biomass and 87 % in grain yield (Fig. 5). Variables related to rainfall extremes were the primary drivers, accounting for 78 % and 83 % of the normalized mean squared error increase, respectively. The SPI of the ten-leaf to flowering phase (SPI_V10-R1), cumulative precipitation around flowering (Prec_R1) and consecutive dry days during the six- to ten-leaf phase (CDD_V6-V10) emerged as the most important variables. Both total aboveground biomass and grain yield were sensitive to the maximum 5-day cumulative rainfall (RX5day) and the extreme hot days intensity (EHD_I30), though their ranking differed. Other rainfall indices, such as seasonal cumulative rainfall (PRCPTOT), were less important. Mulch was moderately important for explaining total aboveground biomass but acted as a noise variable for grain yield. Nitrogen fertilization ranked lowest for total aboveground biomass but was comparatively important for explaining grain yield.

3.3.2. *Partial effects of explanatory variables*

Trends of partial effects, marginalized over other variables fitted to the random forest model, were similar for both total aboveground biomass and grain yield (Fig. 6). A decrease in the SPI_V10-R1 value from –1 to –2 reduced on average total aboveground biomass by 2 t DM ha^{-1} and grain yield by 1 t ha^{-1}. Similarly, total aboveground biomass and grain yield sharply decreased (-20 % on average) when CDD_V6-V10 exceeded 6 days. On the other hand, both variables showed a linear positive response to Prec_R1 up to 45 mm (+45 % for total aboveground biomass and +37 % for grain yield), beyond which they stabilized. An average loss of about 1 t DM ha^{-1} in total aboveground biomass and 0.6 t ha^{-1} in grain yield occurred when RX5day exceeded the threshold of 112 mm or when EHD_I30 raised from 0 to 80 °C day.

Table 3
Maize productivity and N use during the 2022–23 and 2023-24 cropping seasons and ANOVA results for the main effects of rainfall treatments, mulch application, N fertilization levels, and their interactions. Rainfall treatments are reduced rainfall (RR), ambient rainfall (AR), and heavy rainfall (HR); mulch application rates are no mulch (M0) and 6 t DM ha^{-1} yr^{-1} (M6); fertilization levels are no N fertilization (N0) and 80 kg N ha^{-1} yr^{-1} (N80); TAGB is total aboveground biomass at harvest, grain yield is expressed at 12.5 % moisture content. The values in the table represent means ± standard errors (N = 12 for the rainfall treatments, N = 18 for mulch and N fertilization). Means not sharing any similar letter are significantly different according to Tukey honest significant difference test at the 5 % level of significance.

Treatment	2022–23					2023–24				
	TAGB (t DM ha^{-1})	Grain yield (t ha^{-1})	Harvest Index	N accumulated in TAGB (kg N ha^{-1})	N harvest index	TAGB (t DM ha^{-1})	Grain yield (t ha^{-1})	Harvest Index	N accumulated in TAGB (kg N ha^{-1})	N harvest index
Rainfall										
RR	10.3 ± 0.5	3.9 ± 0.2 b	0.33 ± 0.01 b	102.6 ± 6.7	0.49 ± 0.02 b	3.7 ± 0.3	0.6 ± 0.1 a	0.16 ± 0.02 a	28.7 ± 2.1	0.31 ± 0.03
AR	11.8 ± 0.9	5.0 ± 0.4 a	0.37 ± 0.01 ab	116.6 ± 12.7	0.55 ± 0.02 ab	2.9 ± 0.4	0.5 ± 0.1 b	0.14 ± 0.02 a	22.7 ± 3.7	0.30 ± 0.03
HR	10.9 ± 0.6	5.1 ± 0.3 a	0.41 ± 0.01 a	106.6 ± 7.7	0.62 ± 0.02 a	3.6 ± 0.4	1.0 ± 0.2 a	0.22 ± 0.03 a	27.7 ± 4.7	0.40 ± 0.04
Mulch										
M0	11.1 ± 0.6	4.6 ± 0.3	0.36 ± 0.01	108.5 ± 7.8	0.54 ± 0.02	4.1 ± 0.3 a	0.9 ± 0.1 a	0.17 ± 0.02	33.1 ± 3.1 a	0.34 ± 0.03
M6	10.9 ± 0.5	4.8 ± 0.3	0.38 ± 0.01	108.6 ± 7.6	0.56 ± 0.02	2.7 ± 0.3 b	0.6 ± 0.1 b	0.17 ± 0.02	20.5 ± 2.4 b	0.33 ± 0.03
N fertilization										
N0	10.6 ± 0.6	4.4 ± 0.3	0.36 ± 0.01	93.0 ± 6.1 b	0.56 ± 0.02	3.2 ± 0.3	0.5 ± 0.1 b	0.13 ± 0.01 b	20.9 ± 2.5 b	0.29 ± 0.02 b
N80	11.4 ± 0.5	5.0 ± 0.2	0.38 ± 0.01	124.2 ± 7.3 a	0.54 ± 0.02	3.5 ± 0.3	0.9 ± 0.1 a	0.22 ± 0.02 a	32.7 ± 3.1 a	0.39 ± 0.03 a
ANOVA										
Rainfall (R)	ns	**	***	ns	***	ns	**	*	ns	ns
Mulch (M)	ns	ns	ns	ns	ns	***	***	ns	***	ns
N fertilization (N)	ns	ns	ns	**	ns	ns	***	***	***	*
R × M	ns	ns	ns	ns	ns	ns	**	ns	*	ns
R × N	ns	ns	ns	ns	ns	**	***	*	***	ns

The mulch × N fertilization and rainfall treatment × mulch × N fertilization interactions were not significant for any variable. Corresponding lines were dropped from the table.
Significance level: ***, ** and * represent $p < 0.001$, < 0.01 and < 0.05, respectively; ns means not significant.

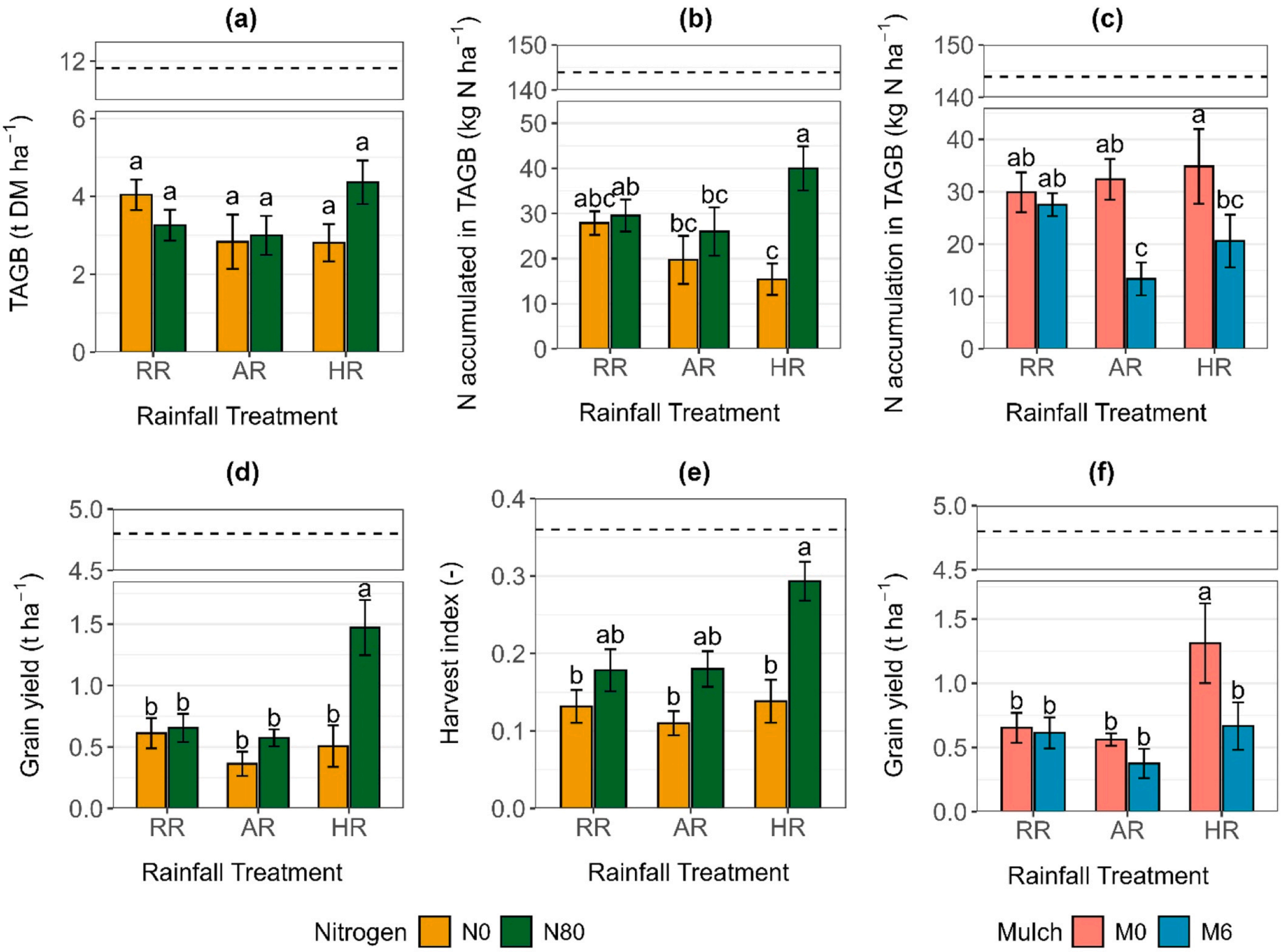

Fig. 4. Effect of rainfall treatment interactions with N fertilization or mulch application on maize productivity and N use during the 2023–24 cropping season for (a) total aboveground biomass (TAGB), (b) N accumulated in TAGB, (c) N accumulated in TAGB, (d) grain yield and (e) harvest index, and (f) grain yield at harvest. For treatments abbreviations see Table 3 legend. Horizontal dashed lines represent values for the yield potential which was non-replicated. Error bars represent standard errors (N = 6). Treatments not sharing any similar letter are significantly different according to Tukey honest significant difference test at 5 % level of significance.

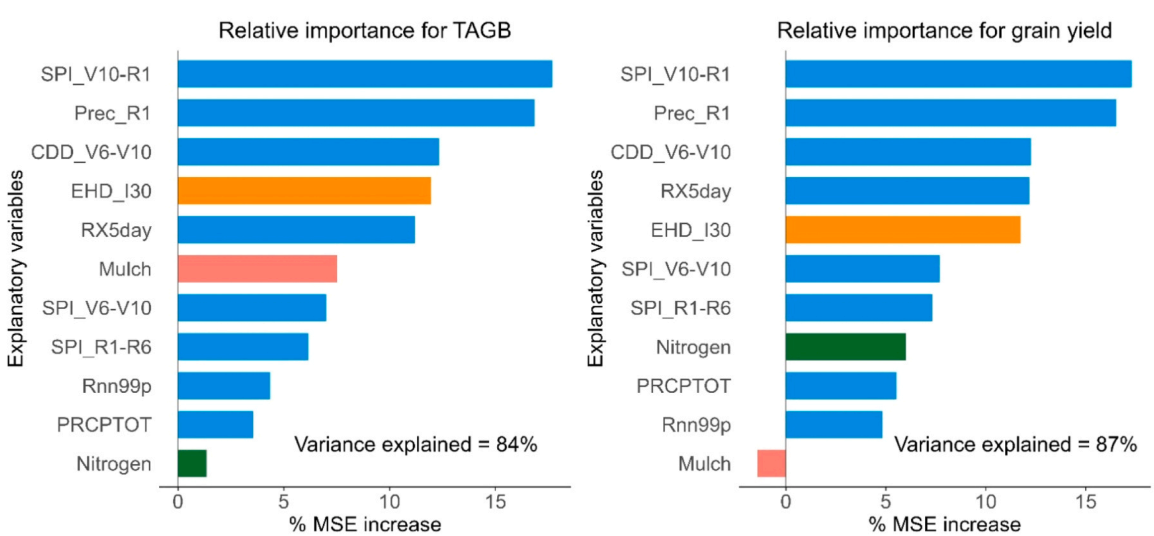

Fig. 5. Variable relative importance in the random forest model for total aboveground biomass (TAGB) and grain yield. Bars indicate the normalized percentage of increase in mean squared error (MSE) for variables related to rainfall (blue) and maximum temperature (orange) extreme indices, mulch application (red) and N fertilization (green). Variables acronyms can be found in Table 2.

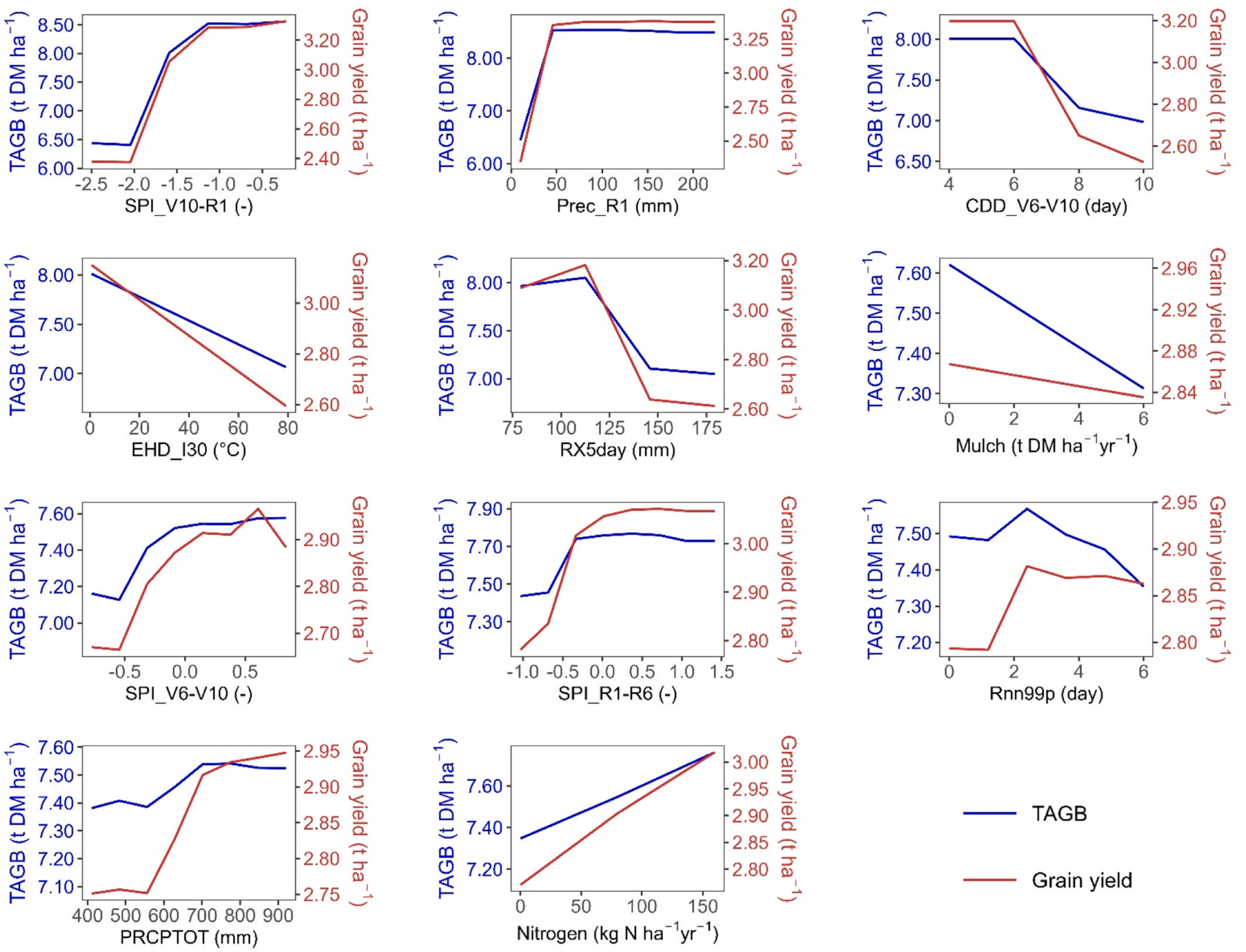

Fig. 6. Partial dependence plots of total aboveground biomass (TAGB) and grain yield in response to each explanatory variable fitted to the random forest model, averaged over other variables.

The other variables had relatively minor effects. Average grain yield and total aboveground biomass slightly increased with higher PRCTOT, SPI_V6-V10 and SPI_R1-R6 (from –0.5–0.5) as well as with N fertilization, while mulch application had a minimal negative effect on both outcomes.

4. Discussion

4.1. Detrimental effects of intra-seasonal rainfall patterns and extremes

Our field experimentation, conducted over two contrasting cropping seasons, revealed that intra-seasonal rainfall patterns and extremes were the dominant drivers of variability in maize productivity and N use in the conditions of this study, outweighing the effects of mulch application and N fertilization. Mulch application failed to buffer the effects of rainfall extremes and even had negative impacts on maize productivity under poorly distributed rainfall. Although total ambient seasonal rainfall in 2023–24 was close to the long-term average, its uneven distribution regarding maize growth stages and water requirements had severe consequences on biomass production and N accumulation. These findings align with those of Marcos-Garcia et al. (2024), who identified the sequence of intra-seasonal dry-wet spell patterns across growth stages as key drivers of maize yield variability in sub-Saharan Africa over recent decades. This is also in accordance with recent findings by Madamombe et al. (2025) who reported that intra- and inter-seasonal variations in rainfall patterns were major maize productivity drivers in semi-arid Zimbabwe, with a greater effect than soil water management practices and planting density. In our study, the atypical pattern of ambient rainfall in 2023–24, induced by El Niño, resulted in most of the season's rainfall occurring as heavy early rains, shortly after crop emergence when maize water requirements were still low (Allen et al., 1998). Beyond the limited ability of the maize crop to effectively utilize this excessive water, it may have also impeded proper root system development (Kim et al., 2024; Li et al., 2019). This was followed by prolonged extreme dry spells from the six-leaf stage onwards, making water the limiting factor, including during the sensitive growth stages of flowering and grain filling (Çakir, 2004). The associated high maximum temperatures may have exacerbated water stress effects, likely contributing to biomass loss through premature leaf senescence and drop (Hu et al., 2023). The importance of the rainfall patterns in 2023–24 was further underscored by the performance of the yield potential treatment, which achieved good levels of biomass and grain yield comparable to those observed in the more favourable 2022–23 season.

By targeting dry and wet spells during specific key crop growth stages, we were able to identify the most influential indices that drove the observed maize aboveground biomass and yield variability, as well as estimate the direction and amplitude of their partial influence. The standardized precipitation index of the ten-leaf to flowering phase was a key determinant, along with the number of consecutive dry days between the six- and ten-leaf stages. These findings are consistent with those of Feng et al. (2018), who reported both indices as highly ranking in explaining inter-annual wheat yield variability in semi-arid Australia. Rainfall amount around flowering was also crucial, reflecting the high sensitivity of maize to water deficit at this stage (Hall et al., 1981). Similarly, hot days intensity, measured as cumulative degree days of maximum temperature above 30 °C, had a significant influence. These two indices have been highlighted in other studies on climate impacts on maize, such as Lobell et al. (2011). These findings support our first hypothesis on the determining role of intra-seasonal rainfall patterns and extremes for maize productivity. They also reinforce the argument made by studies such as Chemura et al. (2022) and Vogel et al. (2019) that intra-seasonal rainfall indices provide a more accurate picture of rainfall impacts on crops than seasonally aggregated metrics such as total rainfall. However, while combining rainfall and management variables in random forest models is a promising approach, extending its use to predictive applications would require independent training and validation on a larger dataset. This should include a wider range of rainfall patterns with relevant indices, as well as different levels of mulch and N inputs beyond the contrasting levels tested in this study. Our ongoing field experiment is expected to generate additional scenarios in the coming years to further test and refine this approach.

4.2. Effects of rainfall reduction and heavy rainfall events

The season's ambient rainfall manipulation in our study through either a permanent 30 % reduction or the addition of two heavy rain events of 100 mm day^{-1} each per season had contrasting effects, mainly on the final allocation of biomass and N to grains. Rainfall reduction affected grain yield inconsistently across the two cropping seasons. In 2022–23, the observed grain yield decrease was linked to a lower number of ears per plant, likely due to limited soil water availability around the flowering stage, which may have led to abortion of some ears (Sari-Gorla et al., 1999). This finding aligns with those from previous field studies which reported that an induced drought during flowering reduces maize grain yield (Renwick et al., 2020; Steward et al., 2019). In 2023–24, a positive effect of rainfall reduction on grain and N yields was observed compared to ambient rainfall treatment. This could be attributed to the rainfall reduction mitigating the adverse effects of soil saturation caused by the early and repeated heavy ambient rains over a short time window. Excess water can saturate soil pores, limiting root growth and functionality, and reducing oxygen availability necessary for respiration and nutrient uptake (Sauter, 2013). The severity of grain yield loss in maize due to waterlogging has been reported to be greatest when it occurs during the early growth stages (Ren et al., 2016; Huang et al., 2022), which coincided with the timing of heavy ambient rains in 2023–24.

On the other hand, the application of heavy rainfall events enhanced grain yield and harvest indices, especially under the dry conditions in 2023–24. In 2022–23, these events were timed post-flowering, coinciding with mild late-season dry conditions, and increased both the dry matter and N harvest indices compared to the ambient rainfall treatment. Although too late to significantly affect the number of ears per plant or grains per ear, they likely enhanced the remobilization of assimilates and nutrients from vegetative organs to the grain, contributing to higher grain size (Borrás et al., 2004). Similarly, in 2024, the higher grain yield and harvest indices under the heavy rainfall treatment may be attributed to increased soil moisture availability following the applied heavy rainfall events, particularly the one applied after the second N top dressing. This supplemental moisture coincided with the onset of mid-season dry spells and probably improved soil N availability and enhanced plant N uptake. This explanation is supported by the predominantly observed yield benefits in fertilized treatments that were associated with a higher number of grains per ear which is a highly sensitive yield component to the N status of maize plants (Ning et al., 2021; Uribelarrea et al., 2009).

Soil N losses might have occurred under the heavy rainfall treatment through increased nitrate leaching, facilitated by the well-drained loamy soil texture of the site, particularly following the first N top dressing (Mapanda et al., 2012), or through nitrous oxide emissions (Shumba et al., 2023) as soil moisture was still high during that period of the season. While these losses might have been compensated by N additions in the fertilized treatments, it could explain why N accumulation in total aboveground biomass was the lowest in the non-fertilized treatments under heavy rainfall at both flowering and harvest. Although most of the literature reports negative impacts of heavy rains on crops (*e.g.,* Fu et al., 2023; Iizumi et al., 2024), only few studies have highlighted their potential benefit. For example, Lesk et al. (2020) observed a slight yield benefit in maize exposed to heavy rainfall ranging from 5 to 20 mm hr^{-1} in the United States. More recently, Heilemann et al. (2024) found a positive relationship between heavy rainfall events of 20 mm day^{-1} during dry periods and silage maize and potato yields in Germany. To our knowledge, our study is the first to report a beneficial effect of heavy rainfall events, involving such large daily amounts, on maize productivity. Our second hypothesis, that rainfall reduction and heavy rainfall events decrease maize productivity and N use, was therefore not fully supported. This emphasizes the critical role of prevailing rainfall patterns surrounding the extreme events, as well as their timing in relation to maize crop development. This was especially evident during the exceptionally dry and hot conditions of the 2023–24 season. Overall, these findings encourage exploring management practices which may help improve synchronization between maize crop development and water availability. In this light, strategies such as optimizing planting densities (Madamombe et al., 2025), or using maize cultivars with different maturity classes (Krell et al., 2021), could help avoid critical water stress periods and reduce yield losses under increasing intra-seasonal rainfall variability.

4.3. Mulch and N fertilization effects and their interactions with rainfall

A major finding of our study is that mulch application did not improve maize productivity or N use. Notably, while no effect was detected in the first cropping season, it significantly reduced biomass and N accumulation in the second cropping season, regardless of rainfall treatment or N fertilization. This outcome contradicts results from previous studies showing that mulch generally has a positive effect on maize grain yield and biomass in the tropics, especially when combined with mineral fertilizer (*e.g.,* Corbeels et al., 2020; Kuonen and Norgrove, 2022). Mulch advantages are usually attributed to improved soil water availability, enhanced nutrient supply, or weed suppression, particularly on low-fertility soils in regions with limited rainfall (Mbanyele et al., 2021; Mhlanga et al., 2021; Ranaivoson et al., 2017). Yet, these positive effects can be offset or even reversed under certain conditions. Short-term negative effects on crop yield have been widely reported, primarily due to N immobilization during residue decomposition (Gentile et al., 2008; Recous et al., 1995), as shown in several meta-analyses (*e.g.,* MacLaren et al., 2022; Sileshi et al., 2025). In our study, we assume that the lack of a mulch effect in 2022–23 was due to the favourable rainfall distribution, and possibly high residual soil N resulting from biological fixation by the preceding sugar bean crop and surface residues it left behind. In 2023–24, soil likely reached field capacity after the intense early rains, before the prolonged drought set in, potentially offsetting any mulch effect on soil water availability (Scopel et al., 2004). In addition, mulch likely exacerbated N unavailability in 2023–24 since maize residues had a high C:N ratio, causing N immobilisation during decomposition (Chaves et al., 2021). Despite the high soil total N content (Table 1), indicating good mineralization potential, N availability may have remained limited due to immobilization processes, with a possible legacy effect from the first season. This effect may have been further compounded by potential N losses due to leaching or denitrification under heavy (ambient and induced) rainfall events (Fig. 4c). These combined factors could explain the more pronounced negative impact of mulch under ambient and heavy rainfall, and the comparatively weaker effect under the reduced rainfall treatment. As a result, our findings suggest that mulch did not buffer the adverse effects of rainfall extremes on maize productivity, leading us to reject our third hypothesis. Overall, our results support the notion that the effectiveness of mulch is highly context-dependent—shaped by interactions between soil N content, rainfall patterns, and crop residue characteristics and management (Palm et al., 2001; Sileshi et al., 2025). While the scope of this study focused on crop-level responses, subsequent studies should investigate changes in soil moisture and N dynamics under rainfall extremes to better understand the mechanisms underlying mulch-crop interactions. Besides, the long term effects of mulching on soil organic matter and N cycling should be investigated (Shumba et al., 2024). Combining field data with soil-crop process-based models offers an alternative to explore a wider range of situations over extended periods and inform more robust, evidence-based adaptation strategies (*e.g.,* Couëdel et al., 2024; Falconnier et al., 2020; Rusinamhodzi et al., 2025).

Maize response to N fertilization was limited under the conditions of this study, with effects primarily seen as increased N accumulation in total aboveground biomass irrespective of the rainfall treatment in 2022–23, and as higher productivity and N use only under the heavy rainfall treatment in 2023–24. The limited response in 2022–23 was likely due to the high residual soil N. The poor response in 2023–24 under the ambient rainfall conditions may be explained by N losses due to the early intense rains, followed by prolonged drought, which limited the ability of the maize crop to utilize the applied fertilizer N. Only under the heavy rainfall treatment, where supplemental moisture helped mitigate drought effects, the fertilizer N uptake improved. This interaction between water availability and N fertilization is well-documented in the literature (*e.g.,* Gonzalez-Dugo et al., 2010; Rusinamhodzi et al., 2011). Our results highlight the economic and environmental risks associated with mineral fertilizer N inputs under variable rainfall conditions and extremes in sub-Saharan Africa (Affholder, 1997; Falconnier et al., 2023b). While N fertilizer use remains critical for increasing maize yields and compensating soil N mining (Falconnier et al., 2023a), combining mineral fertilizers with organic resources, such as manure (Laub et al., 2023) or N-fixing legumes (Vanlauwe et al., 2019) may be a more sustainable approach. Future research should explicitly incorporate the role of rainfall extreme events into the '4 R' fertilizer management framework (Udvardi et al., 2021), with particular focus on evaluating alternative fertilizer forms, application rates, and timing under varying rainfall conditions.

5. Conclusions

This field-based study investigated the impact of intra-seasonal rainfall variability on maize productivity and N use, in interaction with mulch application and N fertilization, under sub-humid conditions in Zimbabwe. The results demonstrate that intra-seasonal dry and wet rainfall patterns and extremes around critical maize growth stages were the dominant factors driving maize performance, far outweighing mulch and N fertilization effects. Maize productivity was observed to sharply decrease under uneven rainfall patterns, despite near-average cumulative rainfall amounts. Rainfall reduction had contrasting effects depending on the prevailing ambient rainfall pattern, while heavy rainfall events improved maize productivity and N use under dry conditions, particularly when combined with N fertilization. Under the experimental conditions, mulch had no buffering effect and instead negatively affected maize productivity under poorly distributed rainfall. These findings highlight that projected future fluctuations in intra-seasonal rainfall patterns will pose a major challenge to efforts aimed at increasing the productivity of rainfed maize in sub-Saharan Africa. They also underscore the limitations of relying solely on seasonal rainfall totals and support the need for using intra-seasonal indices aligned with crop sensitivity to better assess climatic risks. For effective adaptation, rainfall patterns and extremes must be considered alongside agronomic management practices in the design of resilient crop and nutrient management strategies.

CRediT authorship contribution statement

Abderrahim Bouhenache: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gwenaëlle Lashermes:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Hugues Clivot:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization. **Sylvie Recous:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Regis Chikowo:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Armwell Shumba:** Writing – review & editing, Investigation. **Hope Mazungunye:** Writing – review & editing, Investigation. **Emmanuel Matimba:** Writing – review & editing, Investigation. **Gonzague Alavoine:** Writing – review & editing, Investigation. **Olivier Delfosse:** Writing – review & editing, Investigation. **Gatien N. Falconnier:** Writing – review & editing, Project administration, Investigation. **François Affholder:** Writing – review & editing, Resources, Project administration, Funding acquisition. **Marc Corbeels:** Writing – review & editing, Funding acquisition, Conceptualization. **Rémi Cardinael:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Francois Affholder reports financial support was provided by European Commission. Rémi Cardinael reports financial support was provided by European Commission. Rémi Cardinael reports financial support was provided by Agropolis Foundation. Rémi Cardinael reports financial support was provided by Fondation TotalEnergies. Rémi Cardinael reports financial support was provided by French National Research Agency. Gwenaëlle Lashermes reports financial support was provided by French National Institute for Agricultural Research INRAE. Abderrahim Bouhenache reports financial support was provided by the Université de Reims Champagne-Ardenne. Given his role as an Associate Editor for Field Crops Research, Marc Corbeels had no involvement in the peer review of this article and had no access to information regarding its peer review. Full responsibility for the editorial process for this article was delegated to another journal editor. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2025.110126.

Data availability

The data are freely available on the CIRAD Dataverse (Bouhenache et al., 2025).

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