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Assessment of the impact of crop management strategies on the yield of early-maturing maize varieties in the drylands of Niger Republic: Application of the DSSAT-CERES-Maize model

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ABSTRACT

Maize is increasingly becoming important in Niger for use as food and feed. Production is however, faced with several abiotic and biotic constraints. Researchers have developed early-maturing maize varieties that are tolerant to drought, the parasitic weed *Striga hermonthica* and diseases that fit into the short growing production environment. The evaluation and deployment of these varieties would, however, involve costly and time-consuming field trials across the maize production zones of the country. The CERES-Maize model was applied to assess the performance of two early-maturing maize varieties under varying planting windows and nitrogen application in three agroecological zones of the country. The model was calibrated with datasets collected from field trials conducted under optimal conditions (supplementary irrigation and full nutrient supply) at three locations in northern Nigeria. The model was validated with independent data set obtained from field trials conducted in 2020 and 2021 at 4 locations in the Republic of Niger under rainfed conditions. For each variety the treatments were five nitrogen (N) rates (0, 30, 60, 90 and 120 kg ha^{-1}). The results from model calibration and validation revealed that the model accurately reproduced the observed value for days to flowering, physiological maturity, aboveground dry biomass and grain yield with low nRMSE (0.4–12.7%) and high d-index (0.70–0.99) for both varieties. The long-term simulation results (1985–2020) showed that the maize performance was dependent on location, planting window and nitrogen rates. The variety 2014 TZE-Y yielded higher than Brico in all locations for all treatments because it takes longer to mature and accumulate higher dry matter and have higher number of kernels. Simulated yields were generally higher in the Sudan savanna agroecological zone than in the other zones because of higher rainfall and higher clay content of the soil in this zone. The response to N application was influenced by planting window in each agroecological zone. With the exception of two sites, grain yield declined with planting beyond July 14 (PW3) and response to N was not significant beyond this date in the Sudan savanna agroecological zone. Grain yield declined with planting beyond July 7 in the Sahel and Sudan Sahel agroecological zones. There was no further response to N beyond 30 and 60 kg N ha^{-1} when planting is delayed beyond July 7 in the Sahel and Sahel-Sudan agroecological zones, respectively.

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1. Introduction

Maize (*Zea mays*) is one of the most important cereal crops with significant increase in local demand in the Republic of Niger (Niger). Despite the increasing demand, average total annual production remains very low, between 5000 and 6000 tons [1] due to several limiting factors, among which are intermittent drought, poor soil fertility, and poor agricultural practices characteristic of the Sahel. The total production of maize and its products over the last 10 years is estimated at about 30000 tons far below the 45000 tons average imported to satisfy the increasing local demand [2]. Recent growth in chicken production around the urban area also contributes to the increase in local demand for maize grain. According to the Niger Poultry Producers' Association, the national need for maize for poultry feed is estimated at 100,000 tons per year and up to 26,000 tons for the urban commune of Niamey alone [3].

In Niger, maize is mostly cultivated under rainfed conditions in the southern parts of Dosso and Maradi regions in the Sudan and Sudan Sahel Agroecological zones where climatic conditions are favorable for maize production. Also, in lowlands under full or supplementary irrigation in Tillabery, Niamey, Tahoua, Agadez, Diffa, and Agadez regions [4]. Unlike other cereal crops such as millet, sorghum, and rice, research on maize has not received much attention in Niger. Only a few varieties have been registered in the National seed catalogue [5]. Though maize research started since in the 1980s, not much progress has been achieved. The variety P3 Kolo, released in 1984, still remains very popular among farmers [4].

Just like in the dry savannas of West Africa, weather variability is a major challenge to crop production in Niger. The length of the growing season, as well as the amount and duration of rainfall, vary greatly across locations and years [6]. Intermittent drought, which has become more frequent in recent years due to climate change [7], negatively affects crop productivity. In the case of maize, drought coinciding with the flowering and grain-filling stages can cause a serious reduction in grain yield and quality [8]. Variations in rainfall translate into a wide degree of uncertainty regarding the optimal sowing time for farmers in the savanna region [9]. The soils in the dry savanna regions of Niger are also inherently poor in nutrients due to high sand and low clay content [5,10]. The soils in the Sudano-Sahelian zones of the Niger are not only poor in nutrients but are also very heterogeneous [11]. The variability is induced either by management practices or because of differences in texture [12]. Variability in soil characteristics may result in variable crop response and performance. For example, variation in soil depth affects the rooting characteristics of crops, with shallow soils restricting root penetration, resulting in contrasting yield responses to nutrients and moisture [13]. Variations in soil texture, pH, nutrients, organic matter content, and slopes are also reported to limit the efficiency of crop response to fertilizer [14]. The wide variability in the climate and soils in Niger may therefore influence the performance of maize across the zones.

Nitrogen is the most limiting nutrient in soils of Niger due to low biological activities in the soils, low organic matter content, and low nutrient retention capacity [15]. Sub-optimal levels of nitrogen fertilizer application by the farmers in the region [16], have accelerated nutrient mining in this intensifying cropping system [5]. Suboptimal application of nitrogen may reduce nitrogen fertilizer utilization efficiency and maize yield as reported for the savanna regions of Nigeria [17]. In addition to climate variation, drought, and poor soil fertility, infestation of cereal crops with the parasitic weed *Striga harmonthica* is a major limitation to maize production in Niger.

The International Institute of Tropical Agriculture (IITA) and partners have developed several maize varieties that combine tolerance to drought with resistance to *Striga* [18,19]. Some of these varieties are being disseminated along with integrated soil fertility management (ISFM) technologies in diverse maize producing regions of Niger, along with other agronomic practices such as sowing dates and windows, as part of the Climate-Smart Agricultural Technologies (CSAT) project. There is, however, little information on the performance of these technologies in the places they are being promoted. The new early-maturing improved varieties can be valuable to the farmers in Niger, but widespread adoption will be limited. This may be due to both a lack of reliable information regarding the yield potential of the new varieties in the diverse production environments and a lack of knowledge regarding appropriate agronomic management such as sowing dates and nutrient management. Crop management practices for maize, such as planting dates, planting density, and fertilizer application rates, are based on the recommended management practices for current production areas elsewhere in the West Africa subregion. Crop management needs to be adjusted for different environmental conditions to reduce risks associated with climate and production costs [20], and increase crop resilience [21]. Sowing dates [9,22,23], fertilizer application [17,24], suitable crop varieties [25,26], and optimum planting density [27] are some crop management practices that can improve yield in new environments.

Few studies have been conducted in Niger to assess soil fertility management for maize. Pandey et al. [28] compared components of NUE for maize, pearl millet and sorghum on Psamentic Paleustalf soil at three locations in Niger and found out that pearl millet and sorghum have greater N responses compared to maize. Maman et al. [5] evaluated maize agronomic and economic fertilizer use efficiency at Tarna, Maradi and Bengou, Dosso, and reported increased grain yield effects of 20 kg P ha^{-1} at low N rates (20 kg ha^{-1} and 40 kg N ha^{-1}) across locations and years. Though extension services and NGOs, with the support of the CSAT project, are disseminating new improved maize production technologies across the two regions of Niger, the performance of these technologies is not known for most of the areas across the regions. To evaluate the performance of these technologies would require costly traditional agronomic field experiments, which are conducted in specific fields and regions [29,30]. The performance of the technologies is, however, largely site-specific and does not take into consideration variability in soils and climate conditions outside the areas where the technologies have been tested [30,31]. The use of decision support tools could assist decision-making at various stages of maize production, including site selection, evaluation of various management options, selection of crop varieties, and extrapolation and scaling-out of results obtained from a limited area to other areas of the country. The Decision Support System for Agro-technology Transfer (DSSAT) is one of the most widely used crop models [32]. The DSSAT model estimates crop yield and growth based on daily weather, soil profile information, site information, and crop management techniques [33]. In Africa, the CERES-Maize model in DSSAT has been used to:

evaluate maize response to mineral fertilizer on silty clay loam in the northern savanna zone of Ghana [34], simulate nitrogen and phosphorus uptakes as well as soil moisture dynamics in West Africa [35]; provide support for the choice to use micro-dosing of fertilizer in maize production in the Benin Republic [32]; and to determine the optimum planting dates of early and medium maturing maize varieties [29,30] in Nigeria, and most recently, to assess the use of a drought-tolerant variety as an adaptation strategy for maize production under climate change in Nigerian savannas [36]. Despite the robustness of crop models for management decisions, no study has so far attempted to use them to evaluate the performance of improved maize varieties in diverse ecologies in response to crop management practices prior to their large-scale dissemination in Niger. Most crop simulation studies have largely concentrated on millet and sorghum which are the main staples in Niger. Using DSSAT-CERES maize model, we assessed the response of early maturing and extra-early maize varieties to planting windows and nitrogen fertilization in three agroecological zones of Niger. More specifically, the objectives of this study were to: (i) calibrate and validate the DSSAT-CERES-Maize model to test its ability to accurately simulate the performance of two diverse maize varieties in Niger; and (ii) use the calibrated model to assess the performance of the two varieties under varying sowing windows and nitrogen application in three agroecological zones across two regions of Niger.

2. Materials and methods

2.1. Experimental sites

The experiments for model calibration were carried out under optimum water and nutrient conditions at the agricultural research farm of Bayero University, Kano (BUK) (11.983° N; 8.417° E), the Audu Bako College of Agriculture, Dambatta (12.317° N; 8.517° E), and the Institute for Agricultural Research farm, Zaria (11.187° N; 7.147° E) in Nigeria. The experiments were conducted in 2019 and 2020 at BUK, Dambatta and Zaria, and in 2021 at BUK and Dambatta. The experiments for model evaluation were carried out at four sites in Dosso region of Niger in the Sudan savanna agroecological zone (Fig. 1). The locations are Bengou National Institute of Agronomic Research (INRAN) Station (11.981° N; 3.558° E), Borin Ayki (11.939° N; 3.619° E), Gouiwa (11.983° N; 6.979° E), and Tara (INRAN) Station (11.906° N; 3.339° E).

2.2. Soil and weather data at the experimental sites

Soil profile and site description were also conducted prior to each experiment. Soil physical (Sand, silt, clay, pH, OC) and chemical (N, Meh P, K, ca, Mg, Fe, Cat. Exch. Capacity, Exh. Acidity, Zn, Cu, Na, Fe) properties were obtained through soil profile description, sampling and analysis. The results for soil analyses for the calibration sites showed that the soil at BUK had a loamy sand texture, were

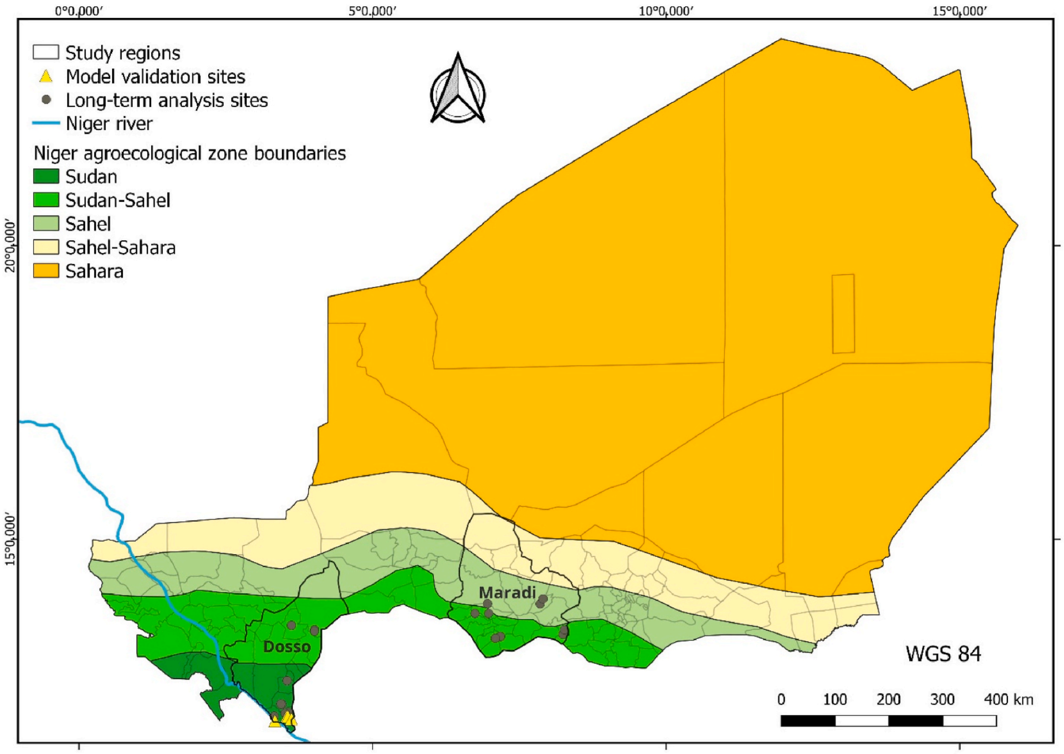

Fig. 1. Map showing study sites in 3 agroecological zones of Niger.

slightly acidic to neutral pH (6.6). Total N was 0.37 g kg^{-1} and available P was 5.62 mg kg-1 with low organic carbon content of 4.4 g kg-1. The total profile water holding capacity at BUK was 0.553 mm/mm at its lower limit and 1.773 mm/mm as its upper limit. The soil at Dambatta, had a sandy loam to loamy sand texture, and was moderately to slightly acidic with pH of 5.7, with low organic carbon content (3.6 g kg^{-1}), very low total N (0.26 g kg^{-1}) and low available P (2.73 mg kg^{-1}). Total profile water holding capacity was 0.548 mm/mm at its lower limit and 0.811 mm/mm in the upper limit. At Zaria, the soil had a silty loam texture and was slightly acidic to neutral pH (5.61), had low organic carbon content (4.6 g kg^{-1}), low total N (0.8 g kg^{-1}) and available P (1.9 mg kg^{-1}). The total profile water holding capacity was 2.045 mm/mm at its lower limit and 0.74 mm/mm in the upper limit.

Dominant soil types at Bengou, Borin Ayki, Gouiwa and Tara (evaluation sites) are the Arenosols (FAO) or Psamnentic Haplustalfs (USDA). The soils are shallow and more gravely on the plateau but are deeper down the slope. The soils pH at the validation sites is slightly acidic and ranges from 5.3 to 6.1. Soil organic carbon content is very low and ranges from 1.2 to 2. 5 g kg^{-1} at Gouiwa, 1.9–3. 8 g kg^{-1} at Borin Ayki, from 1.4 to 4.0 g kg^{-1} at Tara. The available P content is also very low <8 mg kg^{-1} throughout the profiles at all sites.

Daily maximum and minimum air temperatures, precipitation, and solar radiation for each calibration site were obtained from the IITA automated stations (WatchDog 2000 Series Weather Stations, Spectrum Technologies) installed at the calibration sites, which were located closest to each experimental site. For the validation, similar meteorological data were collected for the evaluation sites using Trans-African Hydro-Meteorological Observatory (TAHMO) (TAHMO Co.) station installed at the experimental research station.

In the calibration sites, the total annual rainfall was 606 and 514 in 2019 and 2021, respectively, at Dambatta. In this location, the minimum and maximum air temperatures, respectively were 18.86 °C and 34.7 °C in 2019, 18.6 °C and 35.1 °C in 2021. The total amounts of rainfall at BUK were 592, 840, and 557 mm in 2019, 2020, and 2021, respectively. At BUK, the minimum and maximum air temperatures were 20.8 °C and 33.03 °C in 2019, 20.2 °C and 33.2 °C in 2020, and 20.8 °C and 35.0 °C in 2021, respectively. The total rainfall recorded at Zaria were 870 mm in 2019 and 947.2 mm in 2020. The average minimum and maximum temperatures were 19.35 °C and 32.18 in 2019, 19.39 ° C and 31.95 ° C in 2020 (Figs. S1–3).

For model evaluation experiments in Niger, the total annual amount of rainfall in Bengou was 946.2 mm in 2020. The minimum and maximum air temperatures were 21.8 and 34.6 °C, respectively. The annual rainfall was 700 and 689 mm, respectively, in Borin Ayki and Gouiwa in 2021. The average minimum and maximum temperatures in Borin Ayki were 22.1 °C and 35.5 °C, respectively. While these values were 21.3 °C and 32.3 °C in Gouiwa. At Tara, the total annual rainfall was 867 mm in 2021. The minimum and maximum air temperatures were 20.9 °C and 36.0 °C, respectively, in 2021 (Fig. S4).

2.3. Experimental design and crop management

Two maize varieties were used for the simulation studies. These are 2014 TZE Y (early maturing) and TZEE -Y Pop STR C4 hereafter referred to as BRICO (extra-early maturing). The experimental fields for both calibration and evaluation were disc-harrowed and ridged by tractor disk-plowing, at the onset of the experiment. For calibration, two parallel experiments were conducted on different dates in 2019 at all sites (Kano, Dambatta and Zaria) and two experiments in 2020 at BUK. The calibration experiments were set in a randomized complete block design (RCBD). The plantings were done between the 1st and 2 nd weeks of July in the cropping season across the calibration trials and sites. The recommended N–P–K application rate for maize production was band-applied at a rate of 120–60-60 kg ha^{-1}, respectively. Half of the N, as well as the full P and K dosages, were applied 10 days after sowing (DAS), and the remaining N was applied 35 DAS using urea. The sub-plot size was 3 m by 5 m, with a total of 4 rows per plot spaced at 0.75 m. The harvest area was 1.5 m by 4.5 m. Two seeds were planted at an intra-row spacing of 0.25 m and later thinned to one plant per hill to give a final plant density of 53,333 plants ha^{-1}. Weeds were controlled after sowing using glyphosate and subsequent weeds were controlled manually using a hoe at 5 weeks after sowing. The plots were re-ridged manually using a hand hoe after second urea application. Although the calibration experiments were done during the rainy season, supplementary irrigation was applied whenever necessary.

The experiment for model evaluation was conducted during two rainy seasons (2020–2021). The trials were established on well-drained and responsive soils without fertilizer application in the past two years. The experiments were designed using a split-plot design with three replications. The main plot treatments consisted of five N fertilization rates (0, 30, 60, 90 and 120 kg ha^{-1}). The subplot treatments were two maize varieties used in the calibration experiment. Phosphorus (P_2O_5) and potassium (muriate of potash-K_2O) were band-applied at planting at a depth of about 5 cm and 7 cm away from the plant along the planting row at a rate of 60 kg ha^{-1} at 10 DAS. The nitrogen was applied in two splits according to the treatment at 10 and 40 DAS. For this experiment, the plot size, planting and weeding procedures were carried out exactly as described for calibration experiment. The plots were also re-ridged manually using a hand hoe after second urea application.

2.4. Data collection

Field data were collected from the two middle rows leaving the outside rows and one plant stand at the beginning and end of each row. Parameters measured include days to flowering, days to 95% maturity, aboveground dry biomass (kg ha^{-1}), and grain yield (kg ha^{-1}). At harvest, a quadrat measuring 1.25 m × 1.5 m was placed across the two middle rows of the net plot; all the plants in the quadrat were sampled to determine dry matter. All plants from the quadrat were removed and separated into cobs, stem and leaves. The cobs were shelled and all plant parts were dried in an oven at 60 °C for 76 h to constant weight, weighed and combined to give a aboveground dry biomass. The cobs on plants from the two middle rows were harvested and shelled. The grains obtained from the quadrat were added to those from the two middle rows and weighed to calculate grain yield based on 12% moisture content.

2.5. DSSAT CERES-maize

The CERES-Maize model included in DSSAT was chosen to predict maize yield in Niger because it is one of the oldest, most advanced, and extensively used crop simulation models [37]. The CERES-Maize model is cultivar- and site-specific and operates on a daily time step. The model can also simulate the growth of roots and shoots, the development and senescence of leaves and stems, the accumulation of biomass, and the production of maize grains in relation to weather and soil conditions, crop management techniques, and cultivar parameters [38]. As a result, it can be used to simulate the effects of weather, soil water, soil nitrogen dynamics, and various management practices on maize production. This model has been widely used in many parts of the world at various scales, ranging from the field to the regional scale [39]. Here we used CERES-Maize (DSSAT) v4.7 [40] to assess the impact of crop management strategies on the yield of early-maturing maize varieties in the drylands of Niger. The basic input data required by the CERES-Maize model include daily weather data (minimum and maximum temperature, solar radiation, rainfall and relative humidity), soil data (soil type, soil texture, soil pH, soil moisture, soil organic carbon and soil nitrogen levels), crop management data (crop type, cultivar, planting date, planting density, planting space and rows, fertilizer type and rate of application) and cultivar-specific genetic coefficients [41].

2.6. Model calibration and validation

The model was calibrated with field data collected from twelve experiments for variety 2014 TZE-Y and six experiments for BRICO. The CERES-Maize cultivar calibration requires the estimation of six genetic coefficients (P1, P2, P5, G2, G3 and PHINT) described in Table 1. The model calibration was performed using crop data obtained from rainfed experiments complements with supplementary irrigation when the moisture level of the soil is low using 12 experiments for 2014 TZE Y and 6 six experiments for BRICO described in section 2.3. Initially, the existing cultivar coefficient values for "990003 short season" previously calibrated in the DSSAT, were tested and considered a starting point for our calibration process for both varieties. The GLUE method, as described by He et al. [42] and Li et al. [43] was used to obtain acceptable genetic coefficients for the parameter estimation. The GLUE method procedure was repeated until an acceptable match was found between observed and simulated crop data (days to flowering and maturity, final grain yield, and aboveground dry biomass). Once the model was calibrated, it was validated using the field data from the four experiments conducted at Borin Ayki, Gouiwa, Bengou and Tara. The model was evaluated for days to flowering, days to physiological maturity, final grain yield at harvest, and aboveground dry biomass. To assess the performance of the model, the following statistical indices were considered:

The root mean square error (RMSE) between simulated and observed values was computed as:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)}{n}} \tag{1}$$

Where n is the number of measured datasets, S_i is the simulated data, m_i is the measured data, and $\overline{m}$ is the mean of the measured data.

Normalized RMSE (nRMSE) is expressed as the ratio between the RMSE and the average of the observed data. The model simulations were considered excellent, good, fair, and poor, respectively, based on the nRMSE values of <10%, 10–20%, 20–30%, and >30%.

$$\text{nRMSE} = \frac{RMSE\ X\ 100}{\bar{\text{O}}} \tag{2}$$

where: $\bar{\text{O}}$ *is the overall mean of observed values.*

Index of agreement or d statistic [44], computed as follows:

$$d = 1 - \frac{\sum_{i=1}^{n}(m_i - S_i)}{\sum_{i=1}^{n}(|S_i| + |m_i|)^2} \tag{3}$$

Where: $s_i = S_i - \overline{m}$ and $\overline{m}_i = \overline{m}_i - \overline{m}$.

The d-statistics is a range of values between 0 and 1, the closer the index value is to 1, the better the model agreement.

Table 1
Genetic coefficients of maize varieties used in the study.

Coefficient	Description	Unit	Brico	2014 TZE Y
P1	Thermal time from seedling emergence to the end of juvenile phase	$^{O}C\ day^{-1}$	176.1	215.2
P2	Delay in development for each hour that day-length is above 12.5 h	Day	0.318	0.483
P5	Thermal time from silking to time of physiological maturity	$^{O}C\ day^{-1}$	780.5	832.3
G2	Maximum kernel number per plant	grains ear^{-1}	689.1	736
G3	Kernel growth rate during linear grain filling stage under optimum conditions	mg day^{-1}	6.46	6.18
PHINT	Thermal time between successive leaf tip appearances	$^{O}C\ day^{-1}$	38.9	38.9

2.7. Generating long term simulation

The calibrated CERES-Maize model was used to assess the effects of different planting windows and nitrogen fertilization scenarios in Niger. The simulations were performed at 18 selected sites across the Dosso and Maradi regions. The sites were classified as *Sahel* (Aitadan, Melawa, and Sounsaye), *Sudan-Sahel* (Falwel, Sandarawa, Toukoudawa, Dan Indo, Gabi, Kissa Peul, Madarounfa, Toulou, and Wangarawa), and *Sudan* (Goumandey Koira, Hankoura, Kouka Mai Lamba, Malgorou, Nanilwa, and Toudou Wada) zones as presented in Fig. 1. The locations represent possible maize production areas in Niger.

2.7.1. Soil condition of the simulation sites

Soil profile and site description were conducted in each simulation site. Soil physical and chemical properties were obtained through soil profile description and laboratory analyses as presented in the supplementary data (Tables S1–3). In the three agro-ecological zones, the general low fertility nature of the Sudano-Sahelian Arenosols is reflected in the main soil nutrients and water-holding capacities. In general, available soil P content varies from 0.17 to 3.24 mg kg^{-1} on average, which is far below the critical level of 8 mg kg^{-1} to obtain 90% maximum yield [45]. Organic matter content is mostly less than 4 g per kg, the minimum acceptable range for the tropical/Sahelian soils. However, the OC is generally highest at the surface and decreases with depth. The soils are sandy throughout the soil profile. The lower limit, drained upper limit, saturated water content, and bulk density are characteristics of low clay, silt, and organic matter content of the tropical Ferruginous/Arenosols soils (Tables S1–3).

Soils N, available P and OC content, at the surface, in the Sahel zone (Table S1), are mostly low, ranging from 0.2 to 0.25 g kg^{-1}, 0.49–1.13 mg kg^{-1}, and 2.2–2.3 g kg^{-1}, respectively. Soil pH at Sounsaye, Aitanda and Wangarawa is close to the neutral range particularly at the subsurface. These soils are characterised by their purely sandy nature and clay + silt fraction represent, entirely, on average 10–15% of soil fractions against 17–21% for the Sudan Sahel and 30–44% for the soils in the Sudan. In the Sahel-Sudan (Table S2), the general low fertility nature of the Sahelian Arenosols is also reflected in the main soil nutrients and water-holding capacities. Soil available P content is extremely low and ranges from 0.27 to 4.71 mg kg^{-1}. The OC content ranges from 2 to 3 g kg^{-1}, while N content is also very low. Soil texture is sandy with about 84–88% sand content at the surface except in lowlands with

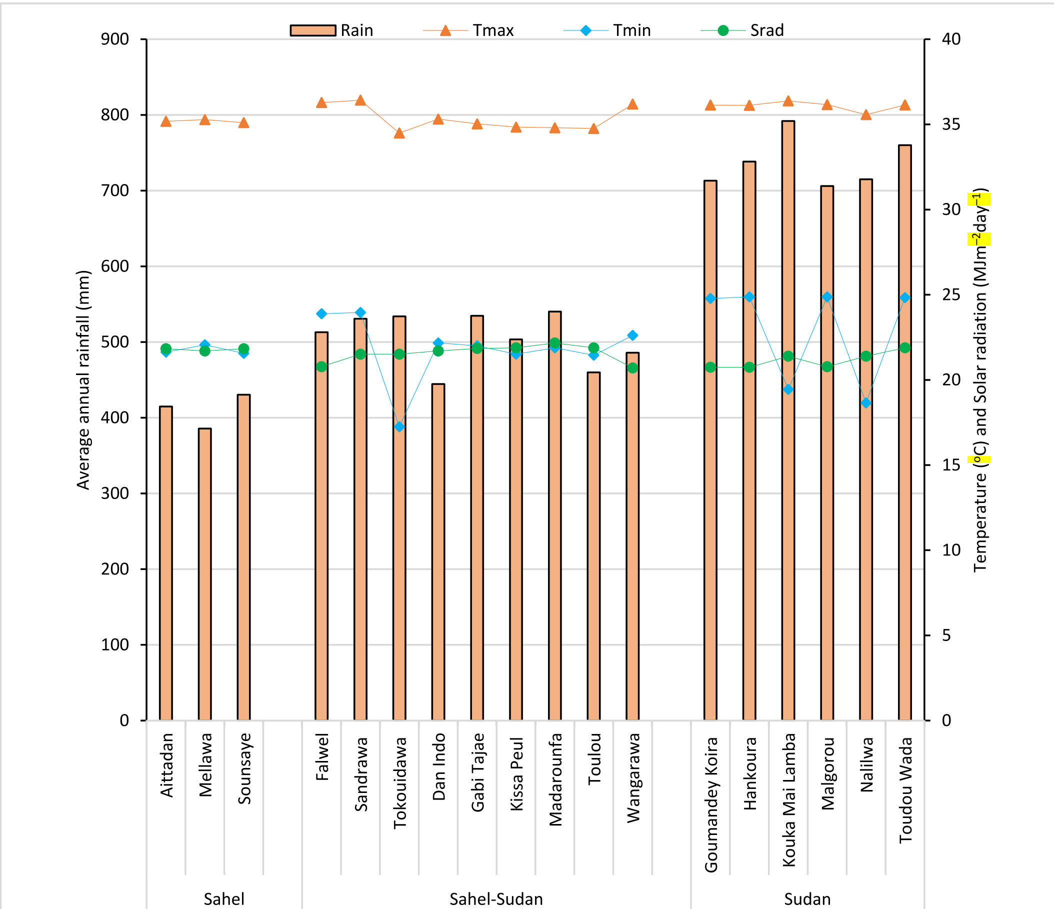

Fig. 2. Thirty-six years (1985–2020) average rainfall, minimum and maximum temperatures of the 18 study sites in Sahel Sahel-Sudan and Sudan savanna agro-ecologies of Niger Republic.

higher clay content. Clay content is solely above 3% along the profile. pH is slightly acidic, but most pH is within the 5.5 to 6.5 favorable range for maize growth and development. Soils in the Sudan zone (Table S3) have N, available P and organic carbon (OC) contents ranging from 0.19 to 0.35 g kg^{-1}, 0.8–4.9 mg kg^{-1}, and 0.17–1.49 g kg^{-1}, respectively. The soils are mostly deep and loamy sand in texture except in the Dallols (Nanilwa) and on the plateau where soils are shallow (40–60 cm in Malgorou). Soils in this zone have higher average clay (6.6%) and silt (19.9%) content compared to the Sudan Sahel (2.1 and 14.6%), and the Sahel (1.6 and 11.2%) respectively.

2.7.2. Weather condition of the simulation sites

The weather data used for the 18 simulation sites in three agroecological zones were sourced and downscaled from gridded Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) [46] and the National Aeronautics and Space Administration (NASA) database available at http://power.larc.nasa.gov/. The daily rainfall data for the seasonal analyses were extracted from the CHIRPS on a global grid with 0.05° × 0.05° spatial resolution. Similarly, the daily air temperature (minimum and maximum) and solar radiation were downloaded from the NASA power database on a global grid with a spatial resolution of 0.5° latitude by 0.5° longitude. Following that, the two datasets were combined to transform each location into a format that the DSSAT model could easily read.

The long-term weather data covered 36 years (1985–2020). The 36-year average rainfall differed significantly among the three agroecological zones as well as the simulation sites within each agroecology (Fig. 2). The average seasonal rainfall in the Sahel zone ranged from 415 to 430 mm for the past 36 years, with Aitanda having the lowest rainfall and Sousaye having the most. The average seasonal rainfall in the Sahel-Sudan zone ranged from 445 to 540 mm, with Dan Indo having the lowest rainfall and Madarounfa having the highest. Over the last 36 years, the average seasonal rainfall in the Sudan zone ranged from 706 to 792 mm, with Kouka Mai Lamba receiving the least and Malgorou receiving the most. The average maximum temperatures in the Sahel across the sites was 35.2 °C, while the average minimum temperatures was 21.8 °C. In the Sahel-Sudan, the average maximum and minimum temperatures over the sites and throughout the climatic period were 35.3 °C and 21.9 °C, respectively. In Sudan, the average maximum and minimum temperatures over the sites were 36.1 °C and 22.9 °C, respectively. Average annual solar radiation was found to be slightly higher in the Sahel region, with an average of 21.8, 21.6 and 21.2 MJ m^{-2} day^{-1} for Sahel, Sahel-Sudan and Sudan zone, respectively.

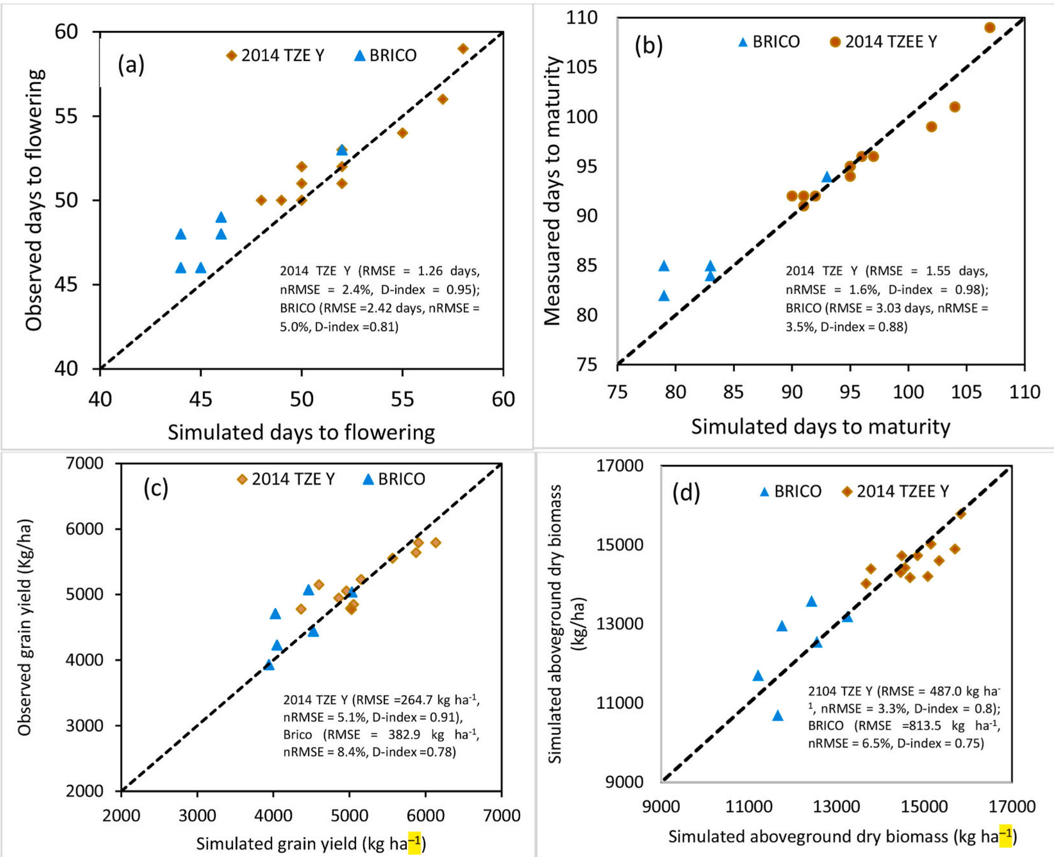

Fig. 3. Observed vs simulated days to flowering (a), days to maturity (b), grain yield (c) and aboveground dry biomass (d) using calibration data sets in Nigeria.

2.7.3. Seasonal analysis

The seasonal analysis was carried out under rainfed–conditions. In total, 1800 simulations were performed considering 5 (five) nitrogen levels, 5 (five) planting windows, 2 two varieties, and 36 years (1985–2020). The simulation was run in each location for each agroecological zone using the daily rainfall, minimum and maximum temperatures, and solar radiation. The daily weather data for 36 growing seasons for each site was imported into the Weatherman utility in DSSAT to create the weather file used for the seasonal analysis. The soil utility software (SBuild) of DSSAT was used to create the soil database using information obtained from the 18 study sites. The simulated crop management included five planting windows: June 24–30 (PW1), July 1–7 (PW2), July 8–14 (PW3), July 15–21 (PW4) and July 22–29 (PW5); five N fertilizer (urea) levels of 0, 30, 60, 90 and 120 kg N ha^{-1}; and two maize (BRICO and 2014 TZE Y) varieties, which represent, respectively, the extra-early and early-maturing groups. The applied N rates were split into two, and the model was set to apply, respectively, at 10 and 40 days after sowing. The model was set to harvest the crop at harvest maturity. Seasonal analysis began one month prior to the scheduled sowing window, with initial conditions reinitiating each growing season.

3. Results

3.1. Crop model calibration and evaluation

Table 1 shows the generated values for the cultivar coefficients for both varieties. The genotypic coefficient P1 was 215.2 °C day for 2014 TZE Y and 176.1 °C day for BRICO. The P2 was <1 day for both varieties. The genetic coefficient P5 was 832.3 °C day for 2014 TZE Y, and 780.5 °C day for BRICO. There was considerable variation between the varieties in G2 and G3. The variety 2014 TZE Y had a

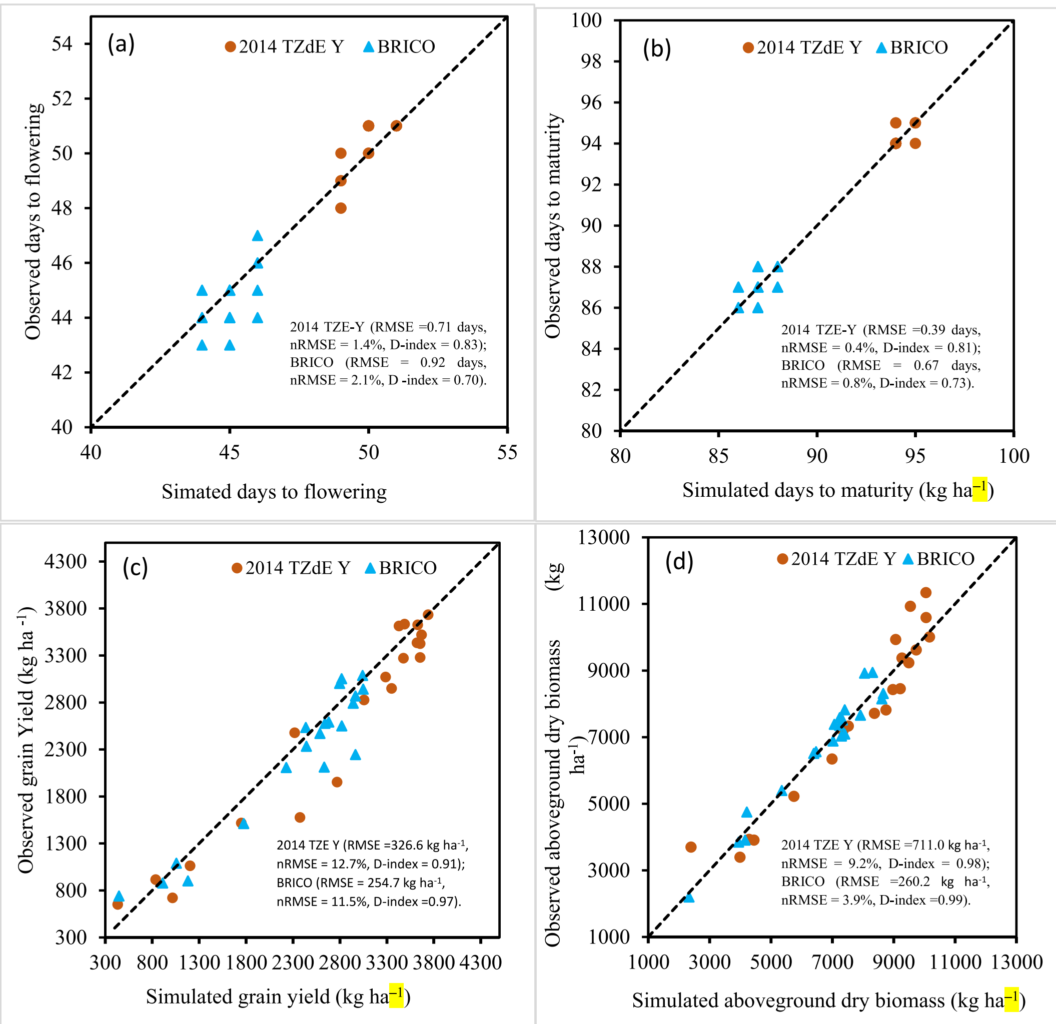

Fig. 4. Comparison of simulated and observed days to flowering (a), days to maturity (b), grain yield (c) and aboveground dry biomass (d) using validation data sets from Bengou, Bourin Aiki, Gouiwa and Tara in Niger Republic. The plants were grown under five N treatments within each location.

higher (736 grains ear^{-1}) maximum kernel number per plant (G2), while BRICO had a higher (6.46 mg day^{-1}) kernel growth rate (G3). However, the thermal time between successive leaf tip appearances (PHINT) was the same (38.9 °C day) for both varieties.

For calibration, all the measured parameters (flowering, maturity, grain yield, and aboveground dry biomass) had low RMSE and nRMSE for both varieties (Fig. 3). The calibration results showed excellent agreement between measured and simulated values, with a nRMSE lower than 10% for all the parameters. The RMSE and nRMSE, for flowering were 1.3 days and 2.4% for 2014 TZE Y and 2.4 days and 5.0% for BRICO, respectively (Fig. 3a). The RMSE and nRMSE for physiological maturity were 1.6 days and 1.6% for 2014 TZE Y and 6.4 days and 3.5% for Brico, respectively (Fig. 3b). For grain yield, the RMSE was 265 kg ha$^{-1,}$ while nRMSE was 5.1% for variety 2014 TZE Y. The RMSE was 383 kg ha^{-1} and nRMSE was 8.4% for variety Brico (Fig. 3c). For the variety, 2014 TZE Y, the RMSE and nRMSE, were 487 kg ha^{-1} and 3.3%, respectively for aboveground dry biomass. For the variety Brico, the RMSE and nRMSE were 813 kg ha^{-1} and 6.5%, respectively (Fig. 3d). In all cases, the D-index values for model calibration were above 0.7, showing good agreement between measured and simulated values for all the parameters.

For model evaluation, the simulated trends of simulated parameters (flowering, maturity, grain yield, and aboveground dry biomass) under different N application rates had good agreement with those of the measured parameters (Fig. 4). For both varieties, the results from model evaluation revealed that the simulated values for days to flowering and physiological maturity were closely related to the measured values, with RMSE less than 1 day for both flowering and physiological maturity, nRMSE below 3% and d values of above 0.7 for both parameters (Fig. 4a and b). The simulated values for grain yield were in good agreement with the measured values (Fig. 4c), with RMSE, nRMSE, and d values of 327 kg ha^{-1}, 12.7% and 0.91 for 2014 TZE Y, and 255 kg ha^{-1}, 11.5%, and 0.97 for Brico, respectively. The model evaluation also indicated strong agreement between simulated and measured values for aboveground dry biomass, with RMSE, nRMSE, and d values of 711 kg ha^{-1}, 9.2% and 0.98 for 2014 TZE Y, and 260 kg ha^{-1}, 3.9%, and 0.99 for Brico, respectively (Fig. 4d). The good agreement between simulated and measured parameters, as indicated by the statistical values, showed that the model could be used to simulate the performance of the maize varieties in the target areas.

3.2. Seasonal analysis

3.2.1. Effects of agroecological zones

The calibrated and validated model was used to simulate the performance of two maize varieties over a 36-year period under 5 planting windows and 5 nitrogen rates across 18 selected sites in the Sahel, Sahel-Sudan and Sudan Savanna agroecological zones across Dosso and Maradi regions of the country. The measured average grain yield of both varieties during the optimum planting window of June 24–30 and the N application rate of 120 kg N ha^{-1} varied significantly among sites within agroecological zones (Fig. 5). Grain yields of both varieties are lower in the Sahel than in other agroecological zones. Differences between the Sudan Sahel and Sudan agroecological zones are not significant for both varieties. In the Sahel agroecological zone, grain yields ranged from 1905 to 2014 kg ha^{-1} for the variety BRICO and 2050–2291 kg ha^{-1} for 2014 TZE-Y. Grain yield was not significantly >2000 kg ha^{-1} in all

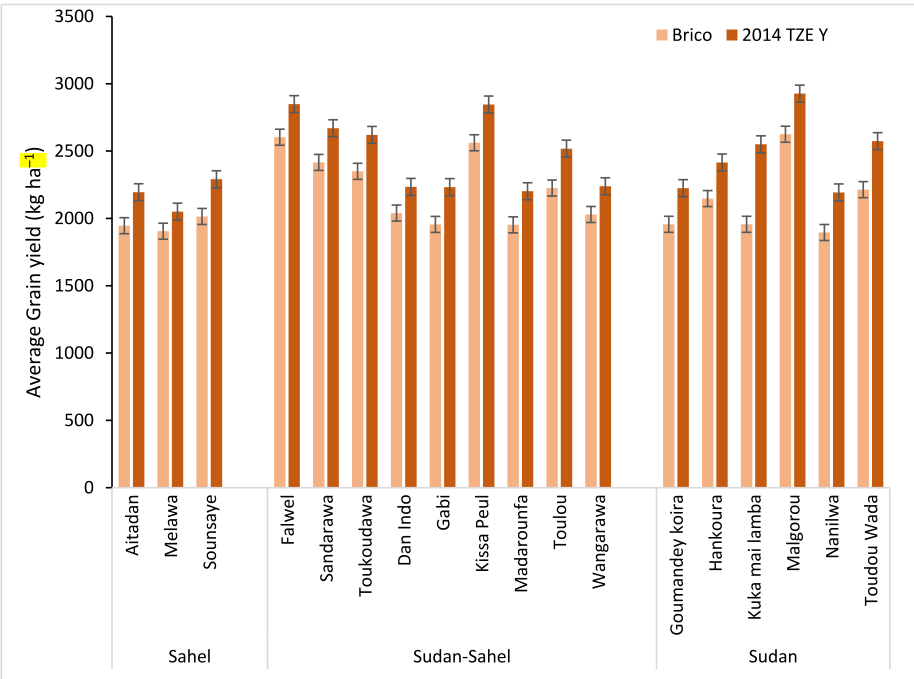

Fig. 5. Effect of maize varieties on average grain yield (1985–2020) in Sahel, Sudan-Sahel and Sudan agroecological zones using first planting window (PW1) and higher N rate (120 kg ha^{-1}).

the locations for BRICO but was significantly >2000 kg ha^{-1} for 2014 TZE-Y in 2 of the 3 locations. Average simulated grain yield is relatively higher in the Sudan Sahel agroecological zone than in the other zones. Grain yield ranged from 1952 to 2603 kg ha^{-1} for BRICO with yields significantly >2000 kg ha^{-1} recorded in 5 out of 9 locations. Grain yields of 2014TZE-Y ranged from 2201 to 2848 kg ha^{-1} with yields significantly >2000 kg ha^{-1} recorded in all the locations. In the Sudan savanna agroecological zone, simulated rain yields ranged from 1895 to 2625 kg ha^{-1} for BRICO and 2193–2926 kg ha^{-1} for 2014 TZE-Y. Grain yield of BRICO was significantly >2000 kg ha^{-1} for 3 out of 6 locations while yield of 2014 TZE-Y was significantly >2000 kg ha^{-1} for all the locations.

3.2.2. Effects of nitrogen application and planting windows

Seasonal analysis over 36 seasons showed that grain yield increased with increasing nitrogen rates for sowing windows PW1-PW3 and maize varieties across all the agroecological zones. The yield increase was greater at N rate of 120 kg ha^{-1} than at the other N rates (Figs. 6–11). While grain yield generally declined with delay in sowing, yield decline was significantly influenced by location and agroecological zone. Response to N was higher in the Sudan Savanna than in the other two agroecological zones particularly with delay in planting. In the Sahel agroecological zone, the pattern of response to N application and planting window was similar for the two varieties for all locations. Yield of the two varieties generally declined with delay in planting beyond PW2. There is also high variability in yield at all N rates with planting beyond PW2. In most of the locations there is no further response to N beyond 30 kg N ha^{-1} when planting is delayed beyond PW1 (Figs. 6 and 7).

In the Sahel-Sudan agroecological zone, grain yield generally declined with delay in planting for all N rates at all the locations.

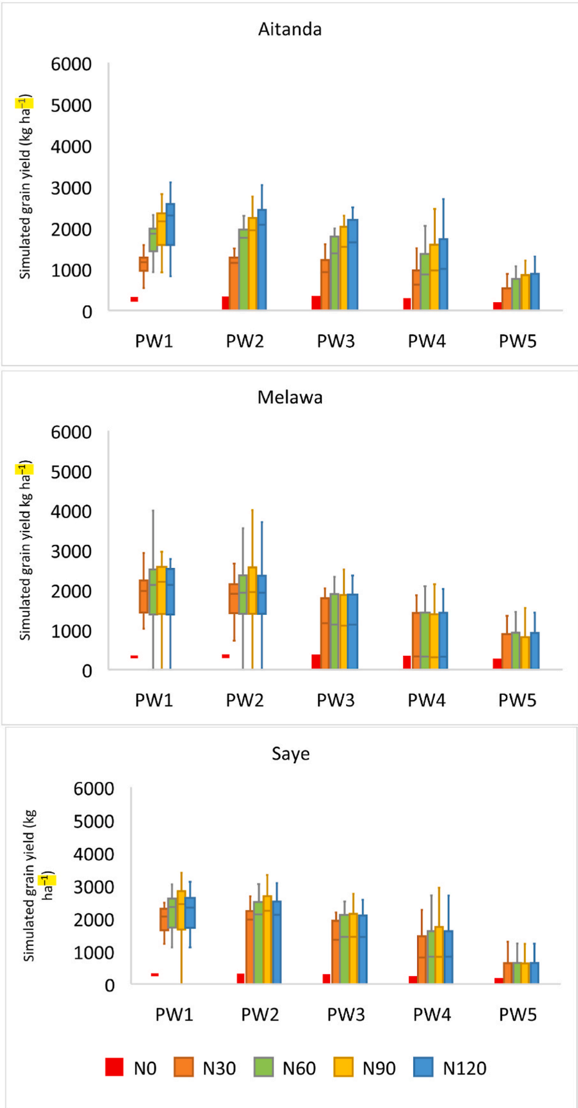

Fig. 6. Simulated grain yield of variety (BRICO) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sahel agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

There was linear response to application of N at five of the nine locations with planting from PW1-PW2. Yield variability was also low at all N rates for these two planting windows. For planting beyond PW2, there was no significant difference between N rates of 90 and 120 kg ha^{-1}. In one of the locations (Kisa Peul), yield was significantly higher at N rates of 30–120 than that at 0 kg ha^{-1} with planting on PW1 beyond which differences among N rates were not significant. The response of the two varieties to N application was not significant beyond 60 kg ha^{-1} in 3 (Kisa Peul, Madarounfa, and Wangarawa) of the locations for all planting windows. The response to N application beyond 90 kg ha^{-1} was not significant when planting is delayed beyond PW2 at all locations for the two varieties. Yield variability was very high with planting beyond PW1 at all locations (Figs. 8 and 9).

In the Sudan savanna agroecological zone, there was significant response to N with increasing application rates. Higher yields were simulated at 90 and 120 kg ha^{-1} than at other N rates at all locations. Stable and significantly higher yields were simulated at two of the six locations (Malgourou and Toundou Wada) for the two varieties at all planting windows and N application rates than at other locations except for the first planting window at Hankoura where response to N was similar to the two high yielding locations. There was high variability and low simulated grain yields at one of the six sites (Hankoura) with planting beyond PW1. Low yields were generally simulated with planting beyond PW3 in the locations except for two sites (Malgourou and Toundou Wada) where yields of over 2000 kg ha^{-1} were simulated at all planting windows. There was high variability in grain yield at three of the sites (Goumandey Koira, Kouka Mai Lamba, and Nanilwa) for all PWs with variability increasing with increasing N rates (Figs. 10 and 11).

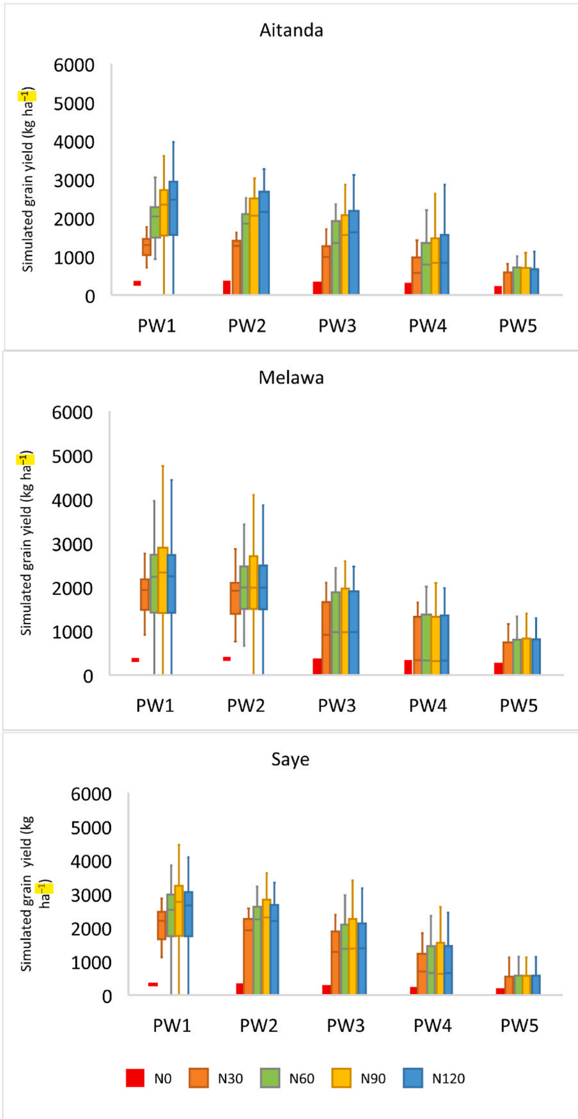

Fig. 7. Simulated grain yield of variety (2014 TZE Y) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sahel agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

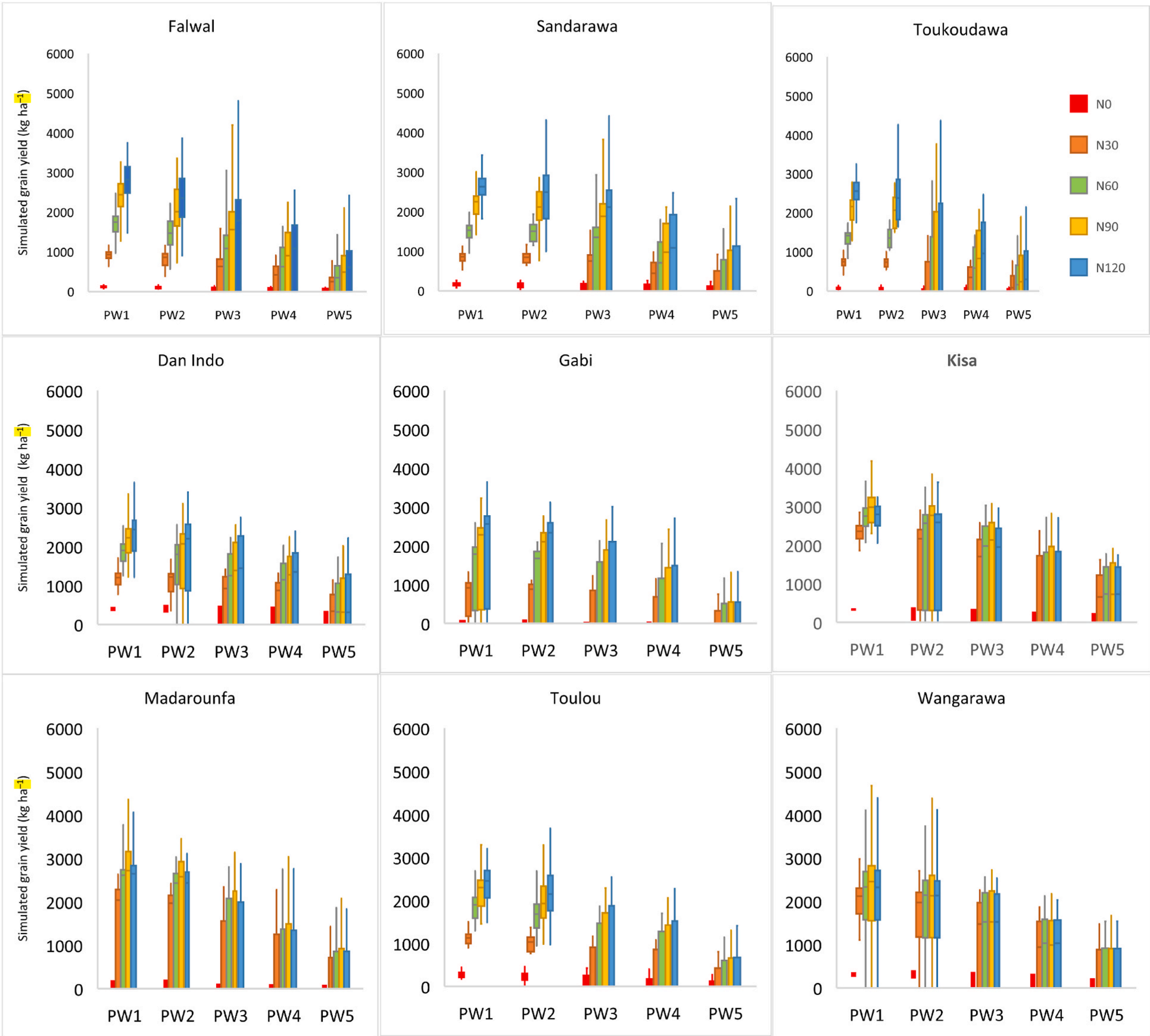

Fig. 8. Simulated grain yield of variety (BRICO) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sudan-Sahel agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

3.2.3. Maize production risk analysis

We assessed the maize production risk across the three agroecological zones using the cumulative probability distribution graphs (Figs. 12–17). We also set the yield threshold that must be met or exceeded for profitable production of maize at ≥ 2000 kg ha^{-1} at the recommended nitrogen application rates of 90 and 120 kg N ha^{-1}. In the Sahel savanna agroecological zone, the desired yield of ≥2000 kg ha^{-1} for both varieties will be achieved in 60–70% of the years with N application of 90–120 kg ha^{-1} and sowing on PW1-PW2 at all the locations. The probability of attaining ≥2000 ha^{-1} will be lower than 40% with delay in planting beyond PW2 for all N rates at all locations (Figs. 12 and 13).

In the Sudan Sahel region, the probability of achieving ≥2000 ha^{-1} varied with location for both N rates and varieties. With N application of 90 kg ha^{-1}, the yield threshold of ≥2000 ha^{-1} will be achieved in 70–90% of the years in 7 out of the 9 locations for both varieties with planting on PW1. With delay in planting to PW2, the yield threshold will be achieved in 70–75% of the years in three of the 9 locations. Delaying planting beyond PW2 will reduce the probability of attaining the yield threshold to 10–55% of the years. At N rate of 120 kg ha^{-1}, the yield threshold of ≥2000 ha^{-1}will be achieved in 70–90% of the years at all the locations for planting on PW1. The desired yield will be attained in 70–75% of the years if planting is delayed to PW2. Delaying planting beyond PW2 will reduce the probability of attaining the yield to <20–55% (Figs. 14 and 15).

In the Sudan Savanna agroecological zone, the yield threshold of ≥2000 ha^{-1} will be achieved in 70–90% of the years with planting on PW1-PW3 at N application rate of 90 and 120 kg ha^{-1} in five of the six locations for both varieties. Delaying planting beyond PW3

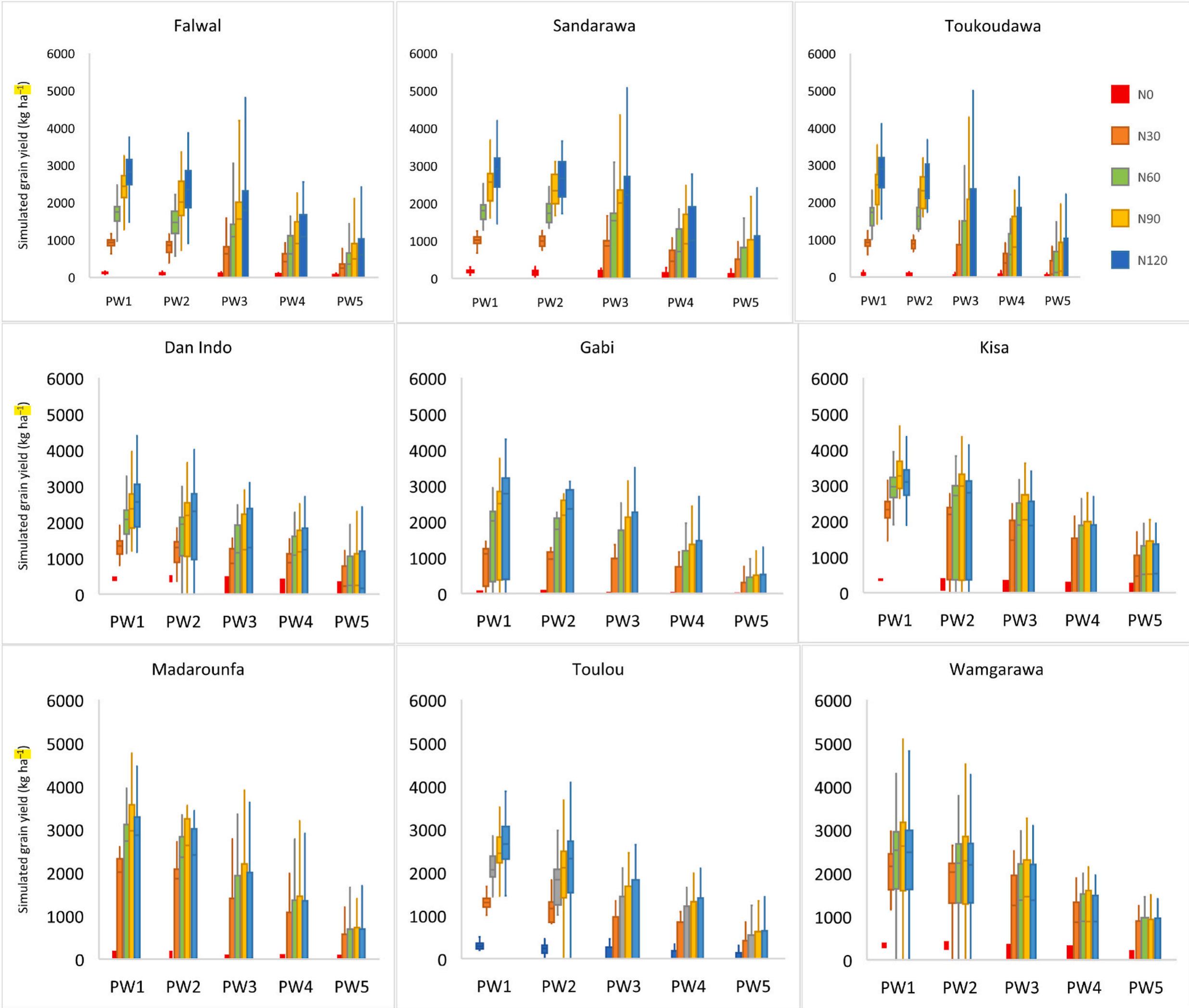

Fig. 9. Simulated grain yield of variety (2014 TZE Y) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sudan-Sahel agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

would reduce the probability of achieving the desired yield to below 40% for both N rates and varieties. Generally the desired yield will be attained in less than 70% of the years at one of the locations (Nanilwa) for both varieties at both N rates and for all planting windows (Figs. 16 and 17).

4. Discussion

In this study, the model calibration results showed excellent predictions for flowering, maturity, grain production, and aboveground dry biomass for both varieties. Generally, the nRMSE was less than 10% for all the parameters. These findings are consistent with those of Adnan et al. [47], who used the DSSAT model to determine the genetic coefficients of different maize varieties in the savannas of Nigeria. They reported nRMSE values of 3.9–10.4% for grain yield, maturity, harvest biomass, and harvest index depending on the variety. The large number of experiments conducted and used for calibration may be attributed to the successful calibration of the CERES-Maize model, as seen by the minimal differences between model-predicted and observed values. The calibrated model, also, accurately predicted flowering, maturity, grain production, and aboveground dry biomass using independent datasets under various N application rates. The statistical indices from the model evaluation also indicated good agreements between observed and simulated values, ranging from excellent (phenology and dry matter) to good (grain yield) prediction for both varieties. This is consistent with the findings of Tofa et al. [30], who showed the robustness of the CERES-Maize model in simulating maize phenology, grain yield, and yield components in Nigeria.

Results show that there is potential to grow maize in Niger but this is dependent on agroecological zones and crop management practices. At the optimum N rate of 120 kg ha^{-1} and planting window of June 24–30, higher yields were simulated in the Sudan

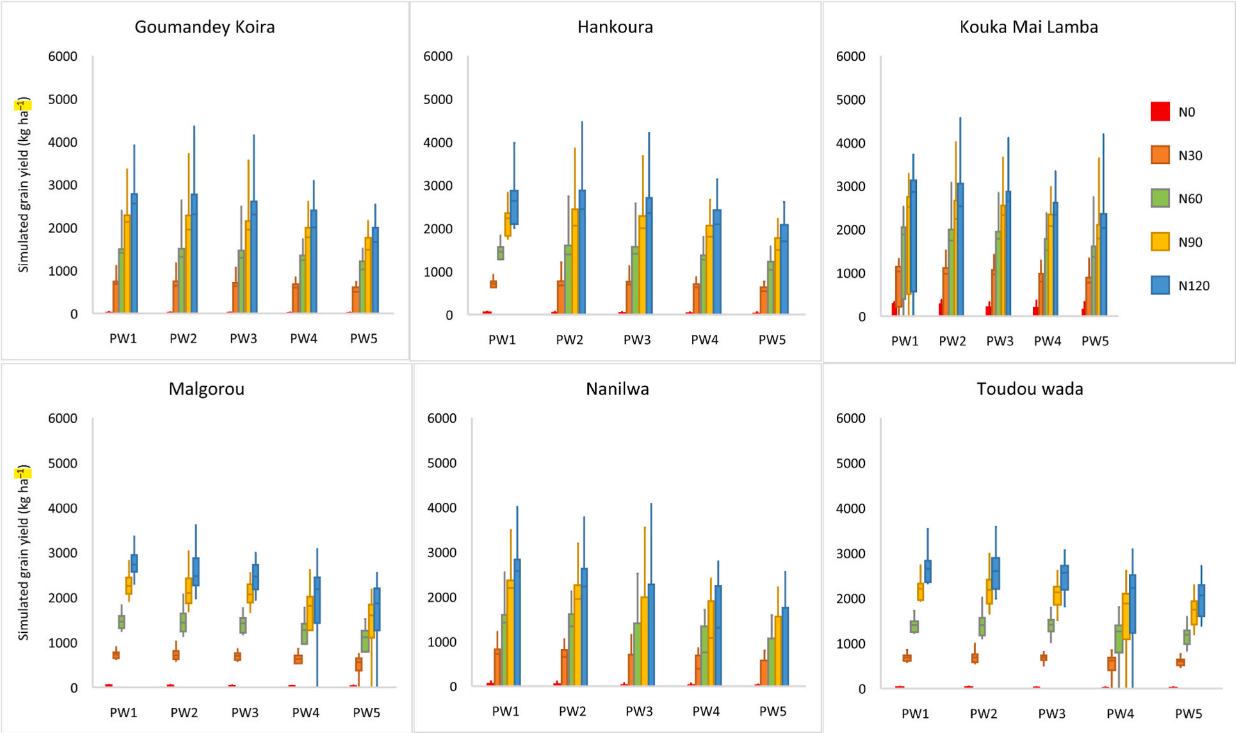

Fig. 10. Simulated grain yield of variety (BRICO) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sudan agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

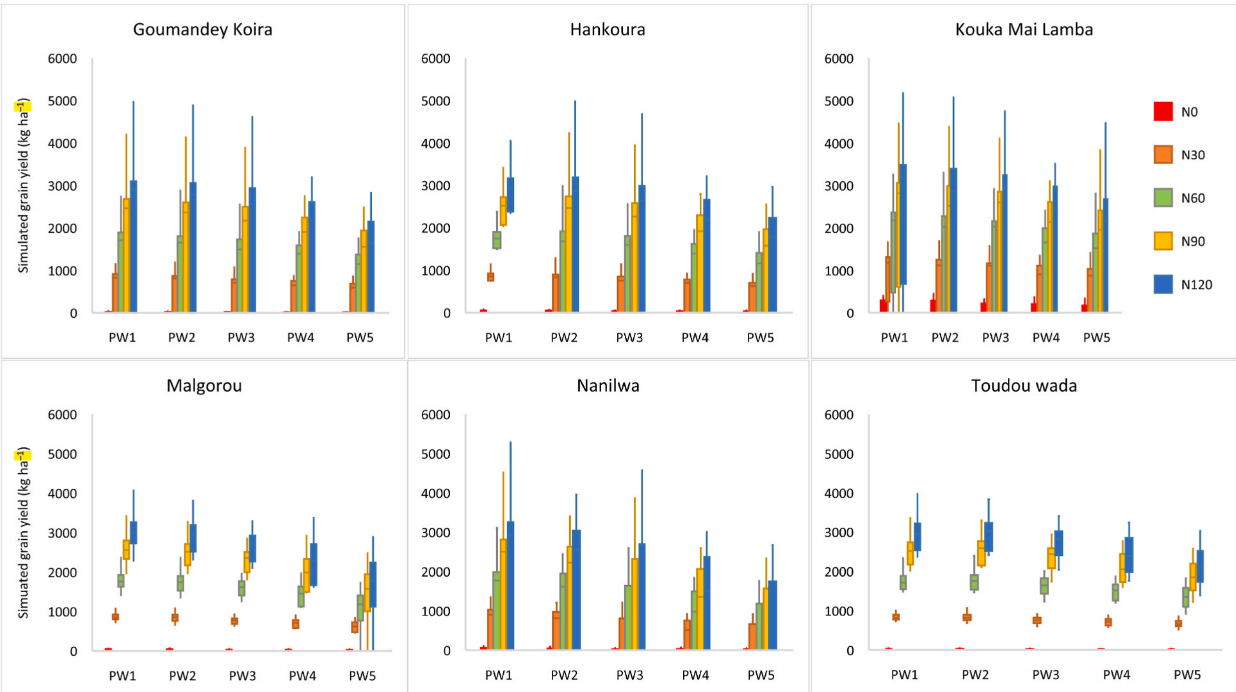

Fig. 11. Simulated grain yield of variety (2014 TZE Y) under variable planting window and nitrogen rate during the last 36 years (1985–2020) in Sudan agroecological zone of Niger Republic. PW1 = June 24–30, PW2 = July1–7, PW3 = July 8–14, PW4 = July 15–21, PW5 = July 22–29.

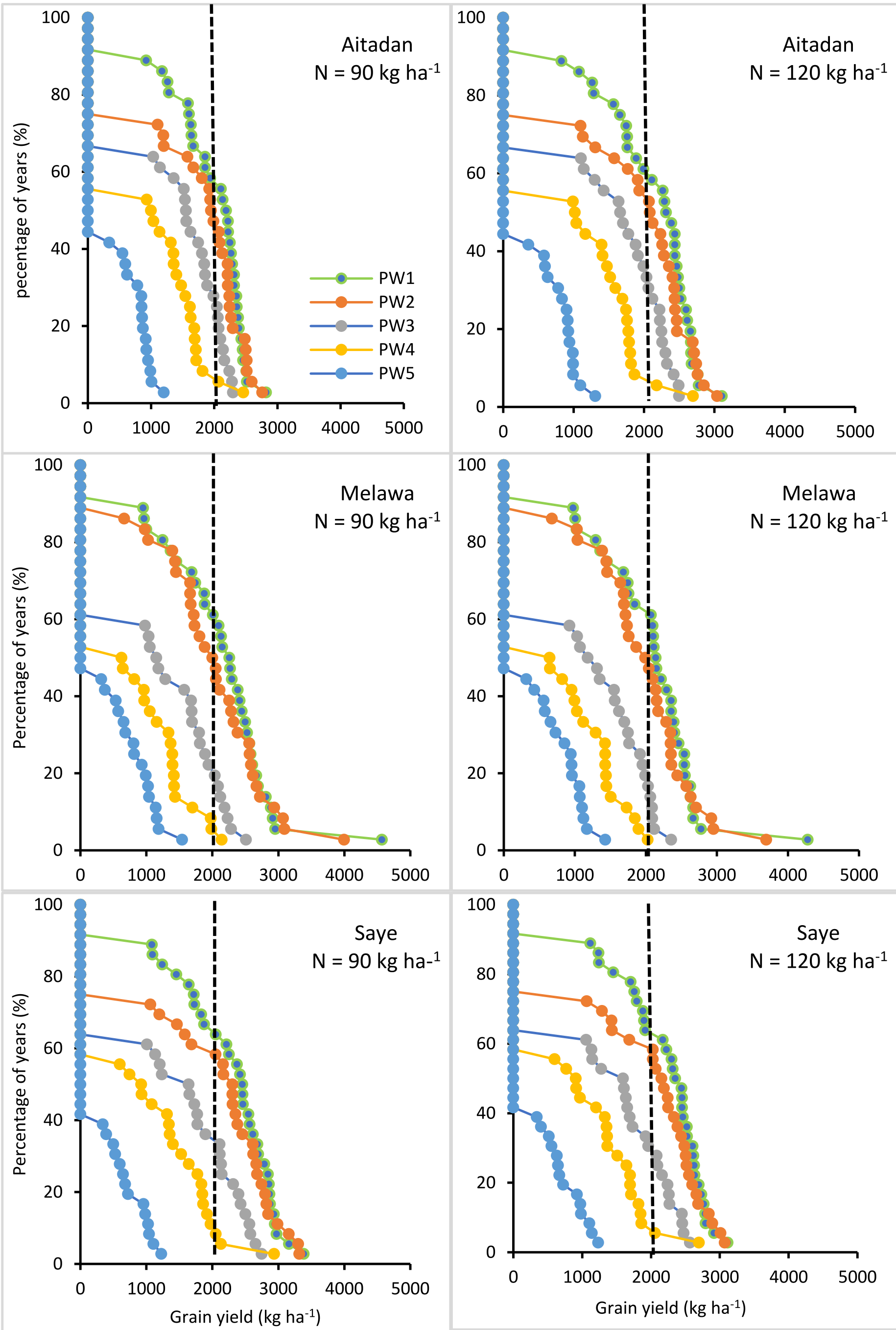

Fig. 12. Cumulative probability distributions of simulated maize (BRICO) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sahel agroecological zone of Niger Republic. PW1 (June 24–30), PW2 (July 1–7), PW3 (July 8–14), PW4 (July 15–21), PW5 (July 22–29).

savanna and Sudan Sahel agroecological zones than in the Sahel agroecological zone because of differences in rainfall and soil conditions. While rainfall ranged from 706 to 792 mm and 445–540 mm in the Sudan and Sudan-Sahel agroecological zones, respectively, rainfall in the Sahel zone was mostly below 400 mm and not sufficient to support maize production. Available evidence indicates that maize as purely rainfed crop may be risky in regions with mean annual rainfall of 400 mm [48]. The soils in the Sahel agroecological zone are also very high in sand (above 80%) compared to the other zones, which may cause low nutrient retention [49]. Though average rainfall was significantly higher in the Sudan (737 mm) than in the Sahel-Sudan (505 mm) agroecological zone, differences in average yields between the two zones were not significant for most of the locations and for the two varieties. This may be due to the

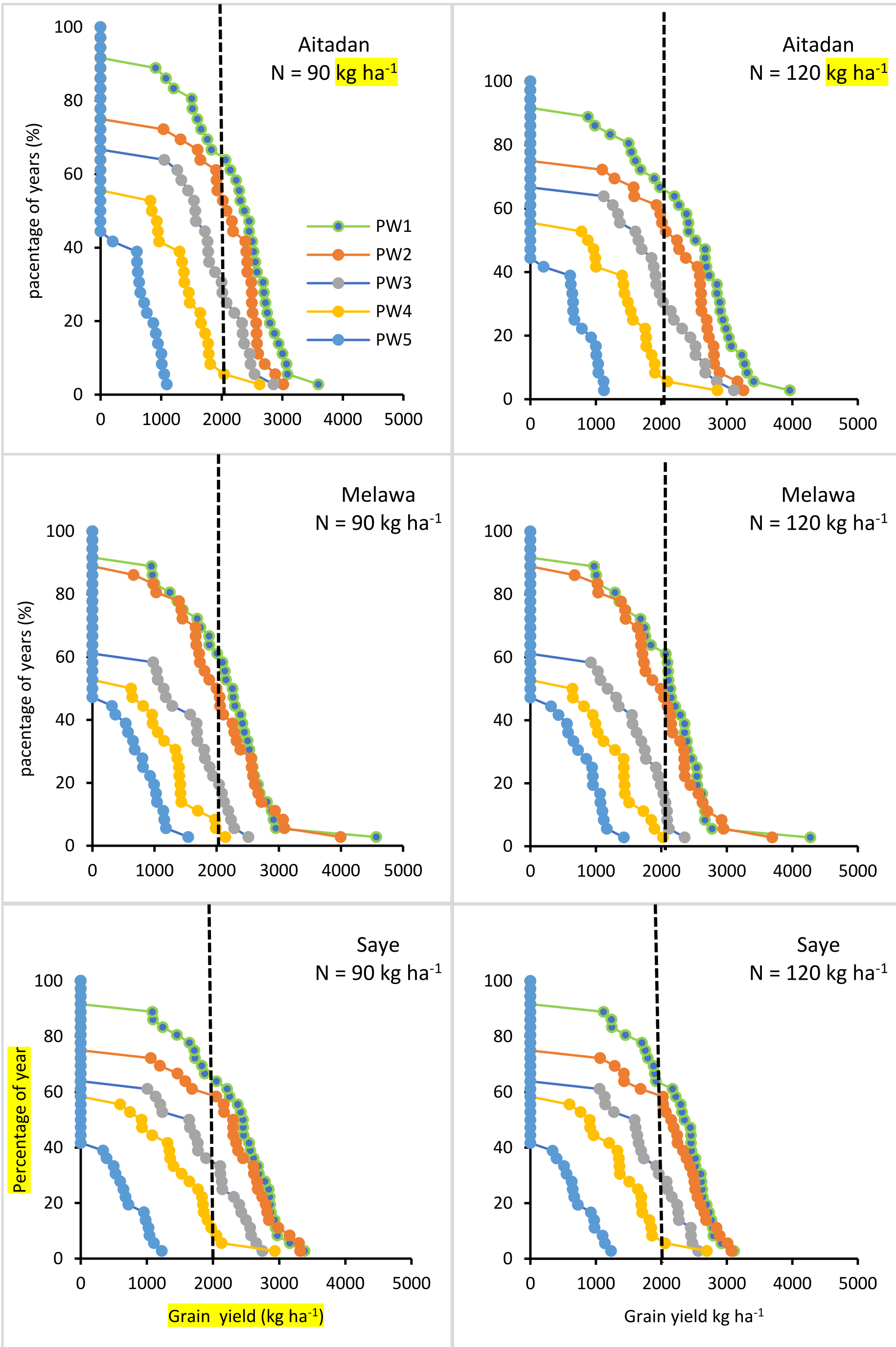

Fig. 13. Cumulative probability distributions of simulated maize (2014 TZE Y) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sahel agroecological zone of Niger Republic. PW1 (June 24–30), PW2 (July 1–7), PW3 (July 8–14), PW4 (July 15–21), PW5 (July 22–29).

comparable soil agrochemical characteristics in these two zones (Tables S1–3). Most of the yield differences were recorded among locations within the agroecological zones. For example, in the Sahel Savanna zone, the least yield was recorded in Melawa, while in Sudan Sahel and Sudan savanna zones, the least yields were simulated at Gabi and Nanilwa, respectively. The differences among locations within the agroecological zones may be due to the heterogenous nature of the soils in the zones [11,49].

In all the agroecological zones, higher yield was simulated for the variety 2014 TZE-Y than for the variety Brico. The higher yield of 2014 TZE-Y may be due to the facts that it produced higher dry matter, higher number of kernels m^{-2} and ear m^{-2} than Brico under

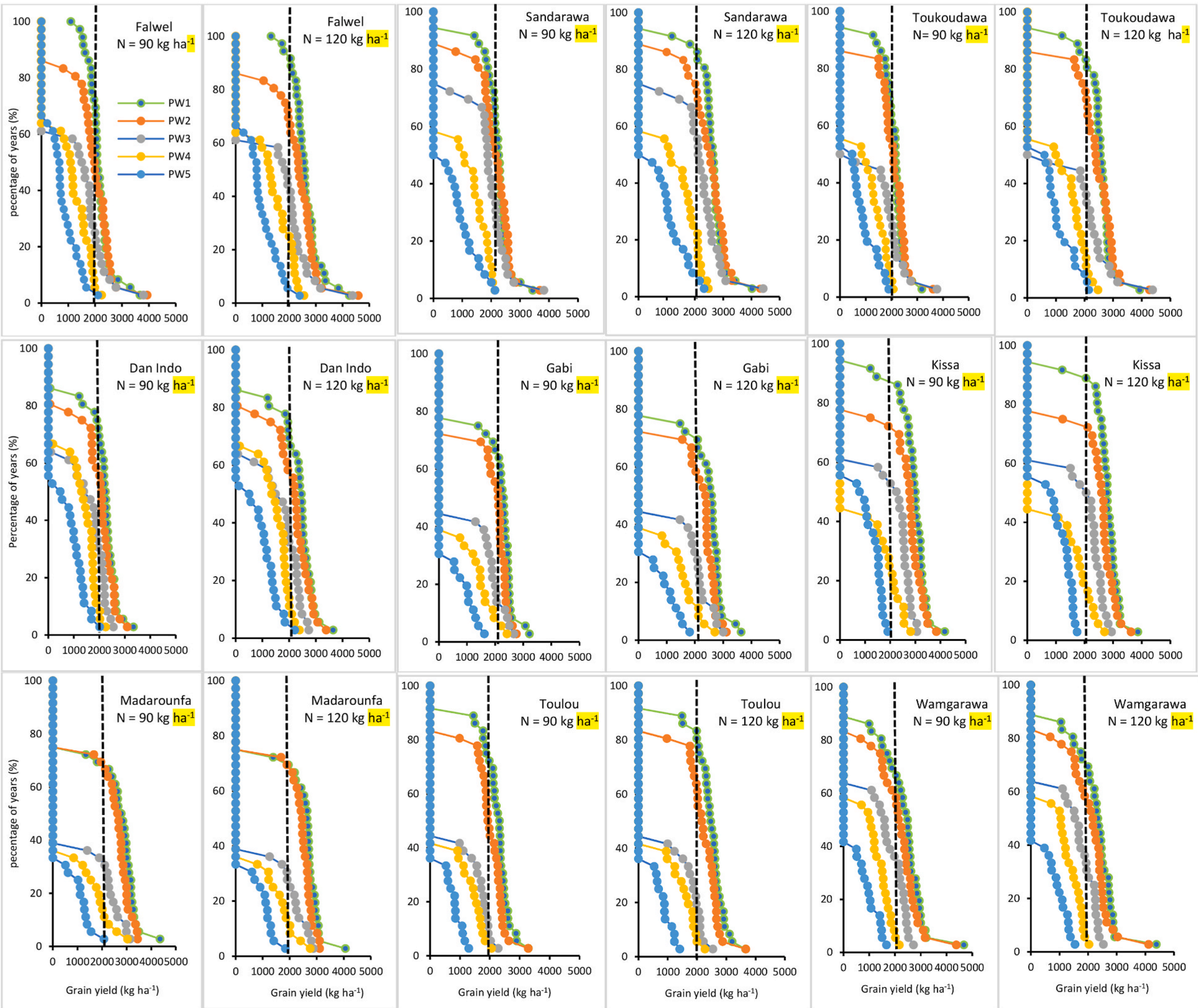

Fig. 14. Cumulative probability distributions of simulated maize (BRICO) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sudan-Sahel agroecological zone of Niger Republic. PW1 (June 24–30), PW2 (July 1–7), PW3 (July 8–14), PW4 (July 15–21), PW5 (July 22–29).

both optimal conditions with supplementary irrigation in Nigeria and under rainfed conditions in Niger (data not shown). The variety 2014 TZE-Y also takes slightly longer to mature under both optimal (95 days) and rainfed conditions (85 days) than Brico (88 and 81 days under optimal and rainfed conditions, respectively).

Seasonal analysis showed that grain yield increased with increasing nitrogen rates but this was dependent on planting window and agroecological zone. While grain yield generally declined with delay in sowing, yield decline was significantly influenced by location and agroecological zone. Response to N was higher in the Sudan Savanna than in the other two agroecological zones with response declining with delay in planting beyond PW3. In the Sahel agroecological zone yield of the two varieties showed high variability at all N levels and generally declined with delay in planting beyond PW2. There was also no further response to N beyond 30 kg N ha^{-1} when planting is delayed beyond PW1. The high variability in yield and lack of response to N with delay in planting may be as a result of drought stress caused by lack of water in the later part of the season. The soils of the Sahel savanna zone are also high in sand and do not retain enough moisture to enhance plant growth. The soil texture plays a dominant role in soil behaviours as its affects water and nutrient retention as well as suitability of soils as a rooting medium [50]. Moisture stress can decrease N uptake from soil and reduce the concentration of N in plant tissue. Nitrogen uptake in dry soil is reduced primarily by the inhibition of root growth along with a decrease in N transport in the soil to the root surfaces [51]. In the Sudan Sahel agroecological zone, there was significant response to N application with planting on PW1-PW2 in most locations. Response to N was however, not significant beyond N rate of 60 kg ha^{-1} in three of the 9 locations for all planting windows probably due to very low rainfall in these locations. Although there is significant response to N in the Sudan savanna, low yields were generally simulated with planting beyond PW3 in the locations except for two sites (Malgourou and Toundou Wada) where yields of over 2000 kg ha^{-1} were simulated at all planting windows. The high yielding

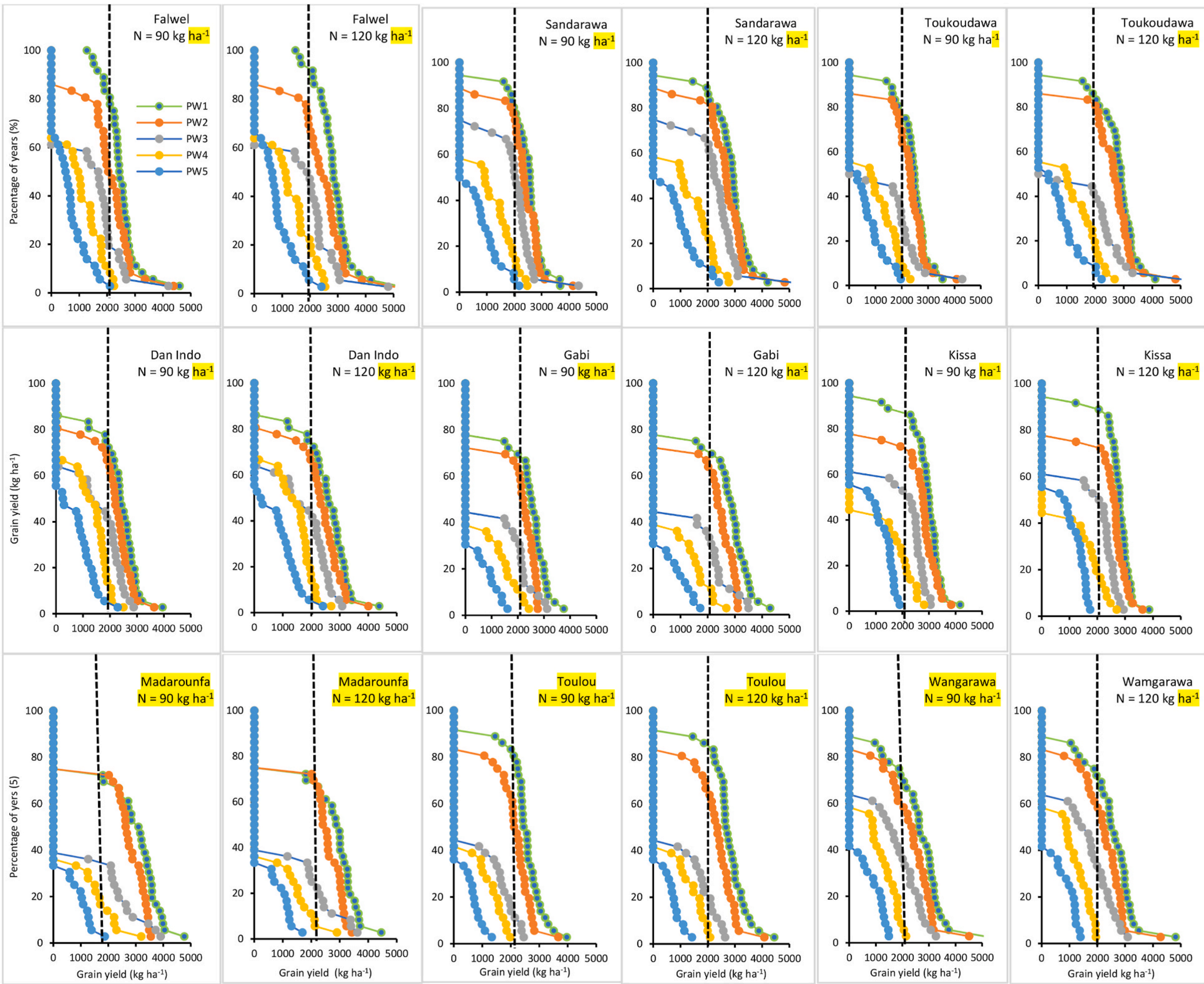

Fig. 15. Cumulative probability distributions of simulated maize (2014 TZE Y) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sudan-Sahel agroecological zone of Niger Republic. PW1 (June 24–30), PW2 (July 1–7), PW3 (July 8–14), PW4 (July 15–21), PW5 (July 22–29).

locations had higher rainfall and high clay content which leads to high nutrient retention. The Sudan savannas usually records higher rainfall than the other agroecological zones in the dry savannas. The zone also has high level of clay which makes it suitable for crop production.

We used N application rates of 90 and 120 kg ha^{-1} to define the desired yield threshold of $\geq$2000 kg ha^{-1} for all the agroecological zones. In the Sahel savanna agroecological zone, the desired yield will be achieved in 60–70% of the years with N application of 90–120 kg ha^{-1} and sowing on June 24-July 7 at all the locations. Delaying planting beyond this planting window would increase the risk of crop failures because of the very low probability (<40%) of attaining the desired yield. The narrow planting window of 13 days and generally low probability of achieving the desired yield even with early planting make the Sahel agroecological zone unsuitable for maize production. The low productivity is associated with low rainfall and poor soils which together make the zone risky for maize production.

In the Sudan Sahel region, the desired yield will be achieved for both varieties for most of the locations with probability of 70–90% if planted on PW1 at both N rates. With N application of 90 kg ha^{-1}, the yield threshold of $\geq$2000 ha^{-1} will be achieved in 70–90% of the years in 7 out of the 9 locations for both varieties with planting on PW1. Delaying planting beyond PW2 will reduce the probability of attaining the yield threshold to 20–55% of the years suggesting that the most suitable planting window is also June 24-July 7 (PW1-PW2). Yields in this zone are higher than those of the Sahel zone because of the better soil conditions. However, the planting window is also narrow making it risky to produce maize in this zone. This narrow planting window suggests that to avoid risks of crop failure, planting should be done timely.

In the Sudan Savanna agroecological zone, the yield threshold of $\geq$2000 ha^{-1} will be achieved in 70–90% of the years with planting on PW1-PW3 at N application rate of 90 and 120 kg ha^{-1} in five of the six locations for both varieties. Delaying planting beyond PW3

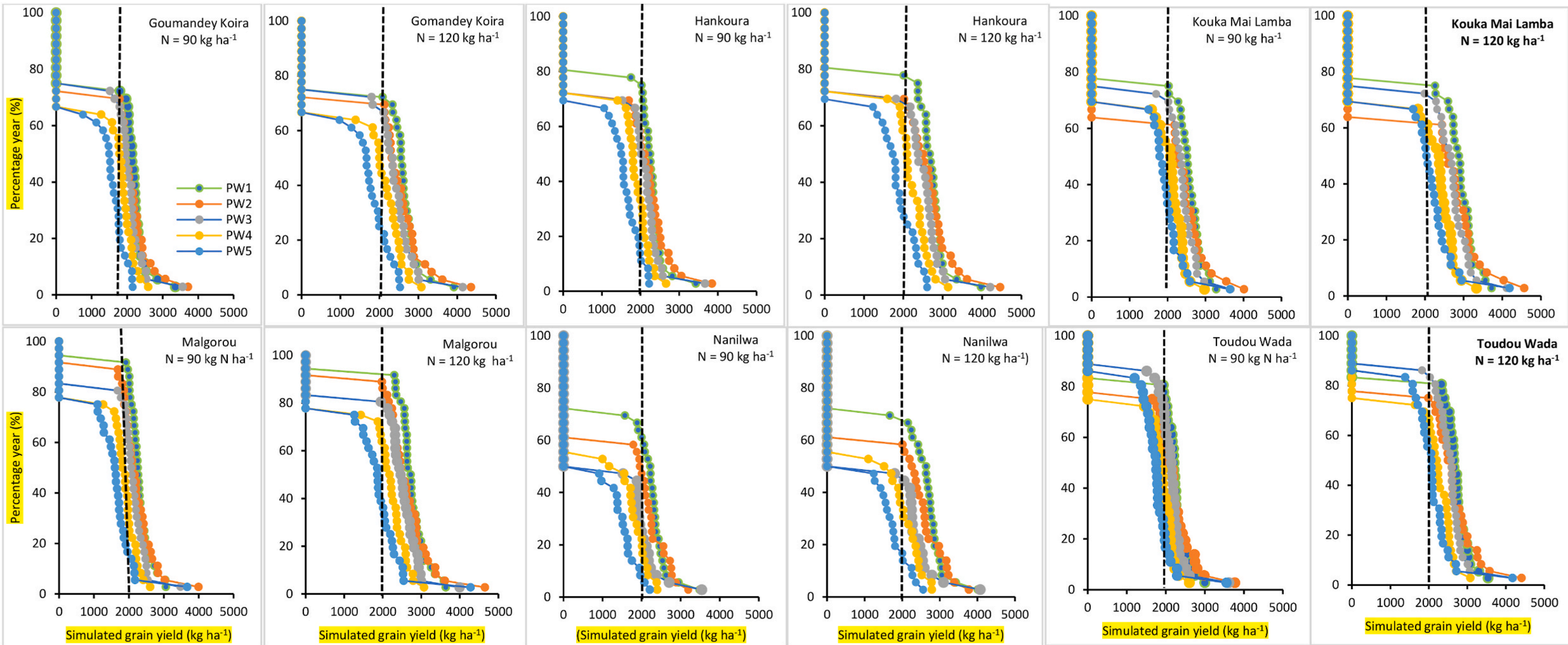

Fig. 16. Cumulative probability distributions of simulated maize (BRICO) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sudan agroecological zone of Niger Republic. —— PW1 (June 24–30), —— PW2 (July 1–7), —— PW3 (July 8–14), —— PW4 (July 15–21), —— PW5 (July 22–29).

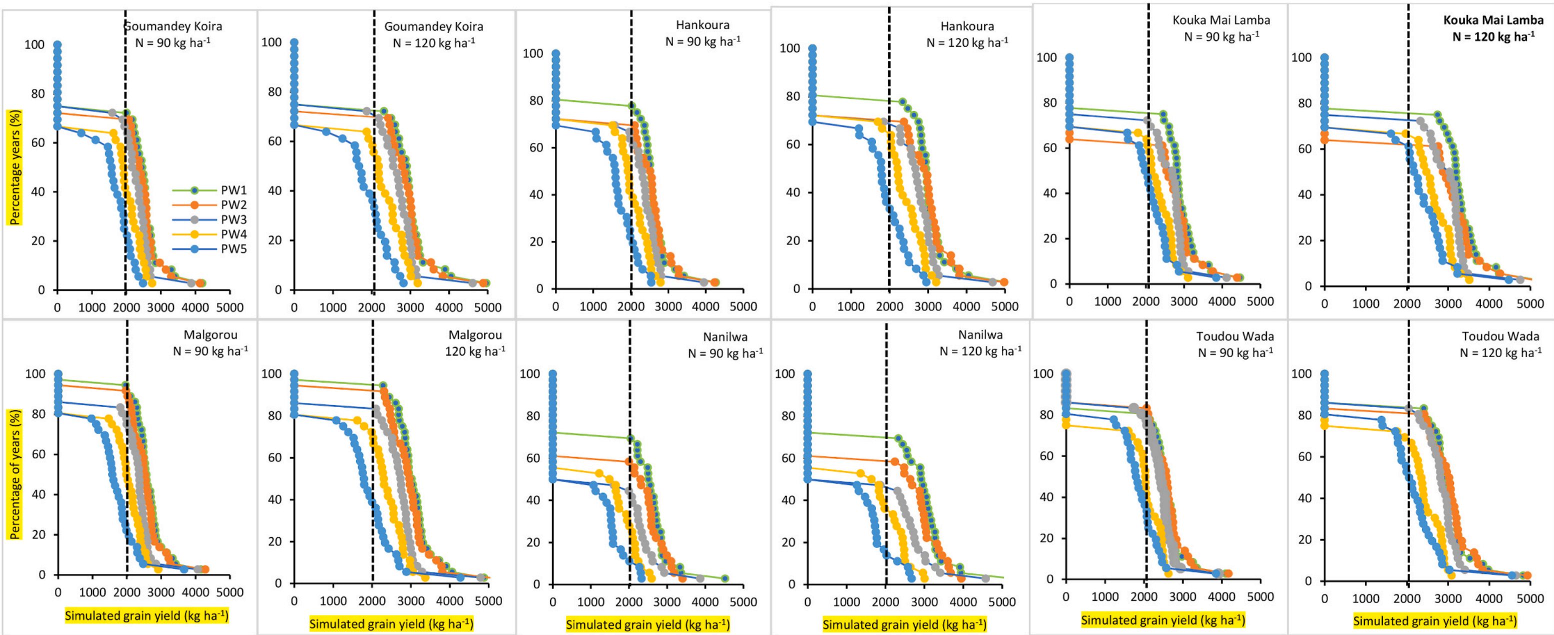

Fig. 17. Cumulative probability distributions of simulated maize (2014 TZE Y) yield under five different planting windows at two higher N applications (90 and 120 kg ha^{-1}) in the Sudan agro-ecological zone of Niger Republic. PW1 (June 24–30), PW2 (July 1–7), PW3 (July 8–14), PW4 (July 15–21), PW5 (July 22–29).

would reduce the probability of achieving the desired yield to below 40% for both N rates and varieties. The results show that there is a window of 20 days for planting maize in this zone. The wide planting window for maize in this zone (June 24-July 14) makes it less risky to produce maize. Generally, the desired yield will be attained in less than 70% of the years at one of the locations (Nanilwa) for both varieties at both N rates and for all planting windows. The high risk of maize production in this location may be associated with poor soil fertility. The soil in this location is sandy and also shallow.

Our simulation results show that soil characteristics played a major role in determining yield and yield differences among sites, in addition to rainfall, planting window and nitrogen application. Because of high sand content in most sites, response to applied N was low across planting dates. Our research did not, however, consider the application of organic manure to enhance nutrient retention and better response of the maize crop. This is a major limitation of this research because the application of organic manure is a major practice in the region given the poor soil fertility in most of the sites. Garba et al. [5] reported increased pearl millet response to N with application of farm yard manure and synergistic effect of fertilizer P with farm yard manure. Further simulation exercises should contain the addition of organic matter in various quantities to investigate their role in the response of the maize crop to applied N over various planting windows.

5. Conclusions

We calibrated and validated the CERES-Maize model and used it to simulate maize performance in three agroecological zones in Niger. Model statistics show that the simulated values agree with the observed ones, suggesting that the model was well calibrated and validated. The model can therefore be used to simulate the response of maize to crop management practices in the selected areas in Niger. The long-term simulation results show that maize performance was dependent on variety, agroecological zone, planting window, and nitrogen rates. Simulated yields were generally higher in the Sudan savanna agroecological zone than in the other zones because of higher rainfall and higher clay content of the soil in this zone. The least yields were simulated in the Sahel agroecological zone because of very low rainfall (Fig. 2) and high sand content of the soils (Table S1) which can reduce nutrient retention in the soil and nutrient-uptake by the plants. The response to N application was influenced by planting window in each agroecological zone. Response to N was higher in the Sudan savanna than in the other two agroecological zones. Although there is significant response to N in the Sudan savanna, low yields were generally simulated with planting beyond PW3 in most locations except for two sites (Malgourou and Toundou Wada) where yields of over 2000 kg ha^{-1} were simulated at all planting windows. In the Sahel agroecological zone there was also no further response to N beyond 30 kg N ha^{-1} when planting is delayed beyond PW1. In the Sudan Sahel agroecological zone, there was significant response to N application with planting on PW1-PW2 in most locations beyond which there was no significant response beyond 60 kg N ha^{-1}. Risk analysis shows that the desired yield of $\geq$2000 ha^{-1} will be achieved in less than 40% and 20–55% of the years if planting is delayed beyond July 7 in the Sahel and Sudan Sahel agroecological zone. This suggest that planting window is narrow in these zones. In the Sudan Sahel zone, the desired yield will be achieved in 20–55% of the years if planting is delayed beyond July 14.

Author contribution statement

Alpha Yaya Kamara, Maman Garba, Abdullahi Ibrahim Tofa, and Mohamed Labo Mohamed: Conceived and designed the experiments and Analyzed and interpreted the data.

Alpha Yaya Kamara, Maman Garba, Abdullahi Ibrahim Tofa, Mohamed Labo Mohamed and Abdoulkader Souley: Performed the experiments.

Tahirou Abdoulaye, Alpha Yaya Kamara, Maman Garba and Abdullahi Ibrahim Tofa: Contributed reagents, materials, analysis tools or data.

Alpha Yaya Kamara, Maman Garba, Abdullahi Ibrahim Tofa, and Mohamed Labo Mohamed and Balkissa Kapran: Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2023.e17829.

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