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RESEARCH

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Assessing the effects of plant density and nitrogen on millet yield in Southern Niger using the CERES-millet model

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Abstract

Background The dryland production environments in Niger Republic (Niger) generate variable crop production risks that reduce crop yields and increase regional food insecurity. Optimal combinations of crop varieties and management are needed to maximize crop water-limited yields in these environments.

Methods In this study, we calibrated and validated the CERES-Millet model using data from field experiments. Seasonal analysis (1984–2020) was carried out in 18 selected sites across the three agroecological zones (AEZs) to test the effects of plant density and N fertilization on grain yield. The treatment included five different plant densities (1.5, 3, 6, 9, and 12 plants m^{-2}) and four N rates (0, 20, 40, and 60 kg N ha^{-1}). Three millet varieties (CHAKTI, HKP, and SOSAT-C88) were compared. Millet production risk was assessed at each AEZ using cumulative probability distribution graphs. The acceptable grain yield required to compensate for the minimum production cost of millet in Niger was set to 975 kg ha^{-1} (75th percentile of the simulated data).

Results The CERES-Millet model reasonably reproduced number of days to flowering (*d*-index > 0.50; RMSE < 2 days), number of days to maturity (*d*-index > 0.50; RMSE < 2 days), and grain yield *d*-index > 0.78; RMSE < 100 kg ha^{-1}) for all the three varieties. The results showed that there was significant response to N (40 – 110% yield increase following N application) and plant density (30–80% yield increase by increasing density above 1.5 plants m^{-2}) in all the AEZs depending on variety. The SOSAT was the most responsive variety to N application and plant density in all AEZs. Under low N application (0–20 kg ha^{-1}) and low (1.5—3 plants m^{-2}) to moderate plant density (6 plants m^{-2}), CHAKTI and HKP had the highest production risks. Increasing N application above 20 kg ha^{-1} mitigate these risks where grain yield was above the 975 kg ha^{-1} threshold representing the minimum production cost for millet in more than 50% of the years under all plant densities except in Sahel where this threshold was only achieved in < 20% of the years. In all AEZs, increasing plant density above 6 plants m^{-2} increases this risk under low to moderate N application, but the downside risk was mitigated when N was applied at high rates.

Conclusion This study demonstrated N application rate and plant density recommendations must be tailored to specific variety and AEZs to maximize grain yield and reduce volatility in Niger.

Keywords Decision support tool, *Pennisetum glaucum*, Production risk analysis, Seasonal analysis, Yield response

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Background

Pearl millet [*Pennisetum glaucum* (L) R. Br.] is an important tropical food cereal grown on approximately 26 million ha in semi-arid regions of Africa and India (Azare et al. 2020). Niger Republic (Niger) is the largest producer of pearl millet in Africa with an average production (2017–2021) of 3.3 million tons on 6.75 million ha of land accounting for 73% of cereal production (FAOSTAT 2023). Pearl millet cultivation dominates food production in Niger as it is the main staple food (Gaoh et al. 2023). Despite the importance of millet as food security crop, productivity is low, yielding about 300–544 kg ha^{-1} on the average (FAOSTAT 2023) and variable (Garba 2014). Nigeriens suffer from a serious food insecurity situation where about 16.5% of the population is considered undernourished (FAO 2023). To address the dire food insecurity situation, it is important to increase pearl millet production in the country. Poor soil fertility as well as frequent droughts and high interannual rainfall variability are the main reasons for the low productivity (Wildemeersch et al. 2015).

In the West African Sahelian regions, including Niger, agriculture faces serious challenges due to poor soil fertility, low soil organic carbon, soil erosion, nutrient depletion, and frequent droughts exacerbated by climate change (Bado and Bationo 2018). Pearl millet, a staple crop in the region, typically receives low fertilizer input, with variable growth responses to nitrogen application (Maman et al. 2018). Farmers often apply manure to a portion of millet fields, but access constraints necessitate external nutrient inputs like fertilizers. In Nigeria, millet yield responded positively to nitrogen application rates between 20 and 100 kg N ha^{-1}, with increases ranging from 16 to 56% depending on location (Ajeigbe et al. 2019). However, the current nitrogen fertilizer recommendation of 46 kg ha^{-1} for millet in Niger, established over two decades ago (Nouri et al. 2017), does not account for soil types, agroecological conditions, or farmer cropping systems, posing limitations to optimizing yield potential.

Generally, grain yields of cereals decrease with increasing sowing density beyond the optimum, but modern varieties are known to tolerate high densities even with low N application (Adnan et al. 2020). In Niger, farmers traditionally use lower plant densities than the nationally recommended spacing of 10,000 pockets per hectare for pearl millet to mitigate moisture stress (Maman and Mason 2013). Farmers typically use wider spacing, averaging 5200 pockets per hectare and many planted at much lower rates, leading to variability between fields (Hiernaux et al. 2009). Studies suggested that increasing plant density can enhance millet grain yield and total dry matter (Bastos et al. 2022; Illiasso et al. 2022). Field experimental approaches have been used to arrive at more appropriate recommendations for nutrient, plant densities and other crop management practices for optimal millet production in the West African Sahelian region (Bado et al. 2022; Bastos et al. 2022; Illiasso et al. 2022; Faye et al. 2023). The field experimental approach is, however, very costly and time consuming (Kamara et al. 2023; Tofa et al. 2020). Moreover, the studies are specific to locations and results cannot be extrapolated to other locations or regions. There is a need to complement field experiments on crop management interactions with simulation models in order to have more spatial coverage and make better variety and location specific recommendations (Adnan et al. 2020). So far, only a few studies have used simulation models to evaluate crop management effects on crop performance in the Sahelian context (Akponikpè et al. 2010). For example, Akponikpè et al. (2010), used the Agricultural Production Systems Simulator (APSIM) model and 23 years weather data in Niger to investigate millet response to N in view of establishing N recommendations better adapted to subsistence smallholder millet farming in the Sahel. Soler et al. (2008) and Mohamed et al (2022) used the CERES-millet model for determining the optimum millet planting dates in Niger. Sultan et al. (2005) also used the SARRAH crop model to simulate attainable yield under optimal soil fertility conditions. Because the studies only considered planting density and nitrogen response separately, it is important to provide information on the interactive response of millet to changes in planting density and N application in diverse regions in Niger. The objectives of this paper are (i) to calibrate and validate the CERES-Millet model for simulating the growth and yield of 3 improved millet varieties in three agroecological zones (AEZ) in Niger (ii) to simulate the response of the millet varieties to planting density and nitrogen application in the three AEZ in Niger using the calibrated model.

Materials and methods

Experimental sites

To obtain crop data for calibration of the CERES-millet model, field experiments were conducted at Goungobon (13°20′6.56″N, 2°18′6.36″E) during 2021 and 2022 rainy seasons, and at Fandou (13°19′57.53″N, 2°19′23.90″E), in 2022. Both sites are located in the Tillaberi region in the Sudan-Sahel AEZ (Fig. 1). The two sites have irrigation facilities scheme to ensure provision of water through supplementary irrigations when the moisture content is below field capacity. Experiments to obtain data for validation of the model were conducted at Magaria (12°58′24.23″N, 8°55′3.36″E) in 2020, Tarna, Maradi (13°27′38.02″N, 7° 6′27.70″E) in 2020 and 2021,

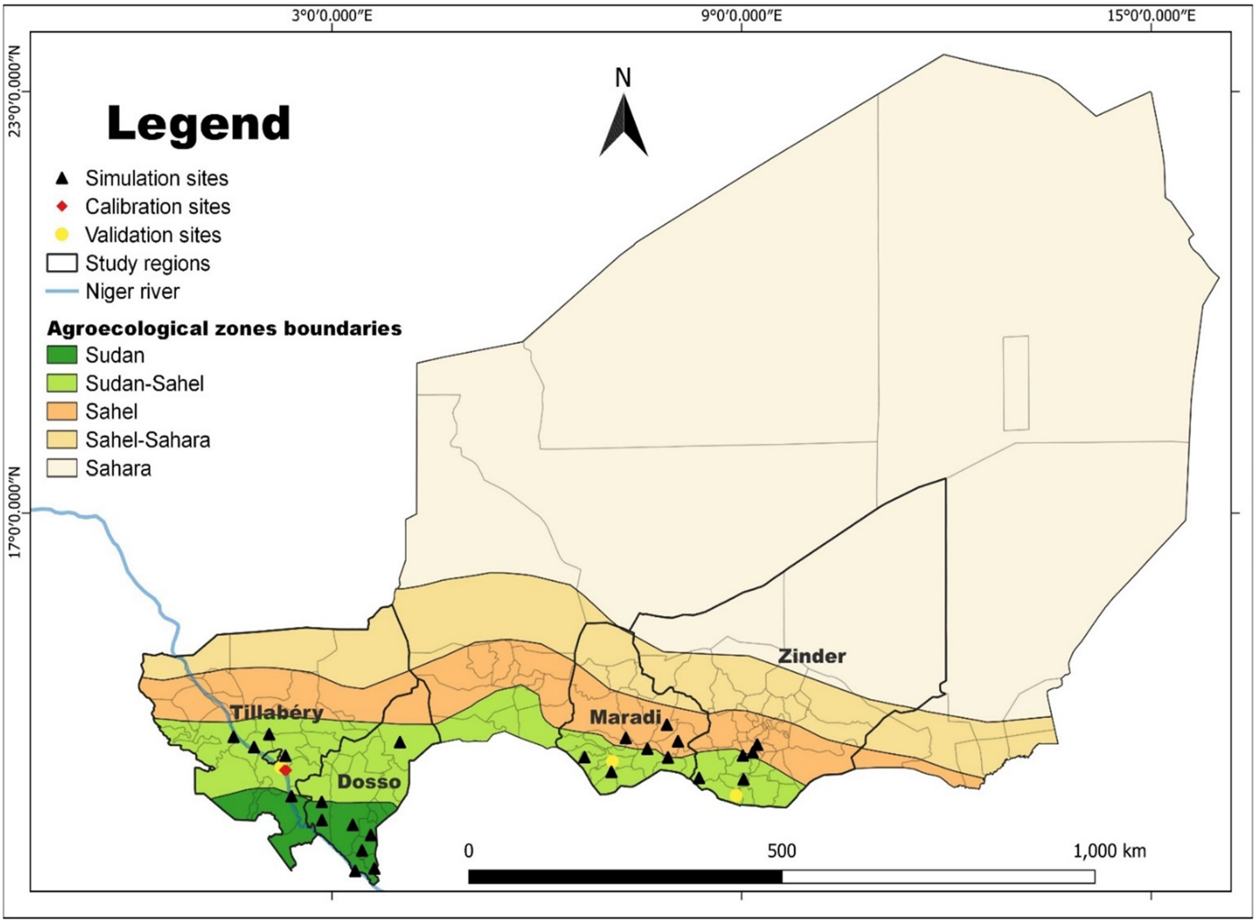

Fig. 1 Map showing study sites in three agro-ecological zones of Niger Republic

and Ndounga, Kollo (13°22′31.71″N, 2°14′51.79″E) in 2020 and 2021 all in the Sudan-Sahel zone.

Weather and soil description at the calibration and evaluation sites

Daily weather data for model calibration and validation were collected from Tahmo weather stations installed near the experimental sites. At the model calibration sites, total rainfall was 310 mm in 2021 and 370 mm in 2022 at Goungobon and 574 mm in 2022 at Fandou. The minimum and maximum air temperatures respectively were 22.1 ℃ and 36.7 ℃ in 2021, 22.5 ℃ and 36.0 ℃ in 2022 at Goungobon and, 21.8 ℃ and 34.4 ℃ in 2022 at Fandou. Total rainfall at the model validation sites was 507 mm in 2020 at Magaria, 650 mm in 2020 and 501.8 mm in 2021 at Maradi, and 728 mm in 2020 and 597 mm at Ndounga in 2021. The minimum and maximum temperatures, respectively, were 19.92 ℃ and 33.12 ℃ in 2020 at Magaria, 20.58 ℃ and 33.54 ℃ in 2020 and 20.34 and 33.74 ℃ in 2021 at Maradi. At Ndounga, the minimum and maximum temperatures were, respectively, 22.13 ℃ and 34.8 ℃ in 2020, and 22.42 ℃ and 35.78 ℃ in 2021.

Soil profiles were dug at each experimental site and profiles described in collaboration with the INRAN (Institut National de la Recherche Agronomique du Niger) soil mapping Unit of the Laboratory of Soil, Water and Plants Analysis-LASEV. Soil samples were collected and analyzed for physico-chemical properties namely sand, silt, clay, pH 1:2.5 H_2O, OC, EC, N, Meh P, Ca, Mg, K, Na, Exch. Acidity, Cat. Exch. Cap., Zn, Cu, Mn, and Fe. The results of soil analyses for the model calibration sites, showed that the soil at Goungobon is sandy loam with OC content varying from 0.3 to 3.5 g kg^{-1} and optimum available P content varying from 23 to 112 mg kg^{-1}. The pH of this soil is slightly acid ranging from 5.72 to 6.79 and the cation exchange capacity of 10.7 cmol kg^{-1} at the surface. Whereas the soil at Fandou contains a sandy surface layer underlain by sandy loam and clay layer from 40 cm depth. Fandou soil is slightly acid with pH ranging from 6.29 to 6.53. The P content varying from 4.5 to 12.2 mg kg^{-1} while N content varies from 0.11 to

0.19 g kg^{-1}. For the model validation sites, soil are the typical Arenosols slightly acid (pH ranging from 5.3 to 6.8), with low OC (1.2–2.0 g kg^{-1}) and very low P contents (1.3–4.6 mg kg^{-1}) at Tarna. Similar characteristics are found with the soils at Ndounga and Magaria soils except the relatively higher sand content usually exceeding 85%. The CEC is generally low (< 3.0 $cmol^{c}$ kg^{-1}) on these model validation sites.

Experiments for model calibration and validation

Three calibration experiments were conducted during the rainy seasons of 2021–2022 at two sites in the Sudan-Sahel AEZ. These trials included three varieties (SOSAT-C88, HKP, and CHAKTI) selected for their good agronomic performance, and wide-spread adoption by farmers. The calibration experiments were conducted under optimal conditions to obtain data for model calibration. For the validation experiment, five planting dates field trials were conducted under natural rainfed conditions. The treatments consisted of four planting dates (15 June, 29 June, 13 July, and 27 July) with same varieties used in the calibration experiment. For both the calibration and validation trials, the plant measurement included the number of days to flowering and physiological maturity and grain yield at harvest. Details on the field experiments and plant measurements can be found in supplementary materials.

CERES-millet model in DSSAT

The DSSAT system contains the CERES-Millet model, a dynamic, process-oriented crop simulation model that simulates crop growth, development, and yield, as well as the Cropping System Simulation Model (CSM) Ritchie et al. (1998). The model integrates a thermal time estimation that is comparable to growing degree days, taking into account the ideal upper and lower limits of temperature where the plant development rates increase linearly with the rise in temperature. Jones et al. (2003) define the minimum soil, weather, management, and site parameters required as model input to simulate a crop. This model simulates the effect of weather, soil water, cultivar, and nitrogen dynamics on crop growth, biomass development, and yield. The CERES-Millet model is a generic model within the CERES-family of models, which adopts a standard format of input and output using the minimum data set as specified for other CERES models the growth, development, and yield of crops are all simulated by this model in terms of weather, soil water, cultivar, and nitrogen dynamics Ritchie (1998).

CSM-*CERES*-millet model calibration

In the process of the calibration, nine cultivar-specific coefficients in the CERES-Millet model were modified for the new cultivars used in this current study. The nine cultivar-specific coefficients (P1, P20, P2R, P5, G1, G4, G5, GT and PHINT) are described in Table 1. The coefficients included those responsible for phenological development (P1, P20, P2R, P5) and those that describe the growth and yield characteristics (G1, G4, GT and G5) (Jones et al. 1998). For the baseline cultivar coefficient, the previously calibrated cultivar coefficient values for "990,001 north variety" was used for the early maturing variety (CHAKTI) and "990,002 middle variety" was used the medium maturing varieties (HKP and SOSAT-C88). Therefore, the default cultivar coefficients in the DSSAT were tested and used as a starting point for our calibration approach. For the three varieties used in the study, the cultivar-specific coefficients were manually calibrated and computed in sequential order, commencing with the phenological development coefficients and progressing to

Table 1 Genetic coefficients of millet varieties used in the study

Parameter	Description	Unit	CHAKTI	HKP	SOSAT
P1	Thermal time from seedling emergence to the end of the juvenile phase (expressed in degree-days above a base temperature of 10 ℃) during which the plant is not responsive to changes in photoperiod	℃ day-1	150	160	160
P20	Critical photoperiod or the longest day length (in hours) at which development occurs at a maximum rate. At values greater than P2O, the rate of development is reduced	(Hours)	12.8	12	12
P2R	Extent to which phasic development leading to panicle initiation (expressed in degree days) is delayed for each hour increase in photoperiod above P2O	℃ day-1	120	119	100
P5	Thermal time (degree-days above a base temperature of 10 ℃) from beginning of grain filling (3–4 days after flowering) to physiological maturity	℃day-1	101	130	140
G1	Scaler for relative leaf size	–	0.7	0.6	0.35
G4	Scaler for partitioning of assimilates to the panicle (head)	–	1.95	1	1.47
PHINT	Phylochron interval; the interval in thermal time (degree-days) between successive leaf tip appearances	℃ day-1	43	43	43
GT	Tillering coefficient, equivalent to G1, but on tillers	–	1.2	1.2	1.2
G5	Potential grain size, mg	–	11	11	11

the crop growth coefficients (Hoogenboom et al. 1992). In the CERES-Millet, development coefficients are determined in degree days (also known as thermal time). The thermal period of a day is equal to the mean air temperature minus the base temperature.

$$\mathrm{GDD} = \sum_{i=0}^{n} \frac{(Tmaxi + Tmini)}{2} - Tbase \quad (1)$$

where GDD stands for growing degree days, Tmaxi is the maximum temperature, Tmini is the minimum temperature, n = number of observations, and Tbase is the base temperature. The cumulative GDD is expressed in °C days.

The genetic specific parameters in the CERES-Millet model were calibrated by comparing simulated and observed data for days to anthesis, days to maturity, and grain yield from the calibration experiments. These coefficients were adjusted using the GLUE (Generalized likelihood uncertainty estimation) by running the model until the fit was observed between the simulated and observed data (Jones et al. 1998).

CSM-*CERES*-millet model evaluation

The model was evaluated using the independent experimental data set obtained from the planting date trials to test the parameters that had already been optimized during the calibration exercise. Various statistical indices were employed, (i) including the Index of Agreement (d-index) (Eq. 2) (Willmott 1982), (ii) root mean square error (RMSE) (Eq. 3). The computed values of RMSE determine the degree of agreement between the simulated values with their respective measured values. the lower the RMSE value the better the simulation of the model.

$$d - \text{index} = -\frac{\sum_{i=1}^{n} (\boldsymbol{m_i} - \boldsymbol{S_i})^2}{\sum_{i=1}^{n} (|\boldsymbol{S_i}| + |\boldsymbol{m_i}|)^2} \quad (2)$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\boldsymbol{m_i} - \boldsymbol{S_i})^2}{\boldsymbol{n}}} \quad (3)$$

where Si = simulated value, mi = measured value, and n = number of observations.

Weather and soil condition of the simulation sites

Thirty-six-year weather data (1984–2020) for 18 sites across three AEZ in Niger were used for the seasonal analysis. The data were sourced and downscaled from gridded Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for daily rainfall (Funk et al. 2015) and National Aeronautics and Space Administration (NASA) database http://power.larc.nasa.gov/. For daily minimum and maximum air temperature and solar radiation. The rainfall data were extracted from the CHIRPSmat at 5.5 km resolution and then merged with data (daily minimum and maximum air temperatures, and daily solar radiation) from NASA database. R scripts created was used to append data for CHIRPS and NASA power. The 36-year average rainfall varied significantly in the three AEZ (Fig. 2). In the Sahel savanna AEZ, seasonal average rainfall varied from 384 to 448 mm across the sites. The average maximum temperature was 35.0 ℃, while the average minimum temperature was 20.9 ℃. The average seasonal rainfall in the Sahel-Sudan AEZ ranged from 418 to 615 mm, with average maximum and minimum temperatures of 35.8 ℃ and 20.2 ℃, respectively. In the Sudan savanna AEZ, the average rainfall ranged from 653 to 919 mm. The average maximum and minimum temperatures over the sites were 35.5 ℃ and 21.8 ℃, respectively.

The soil physical and chemical properties obtained after laboratory analyses are presented in supplemental tables (Tables S1-3). In the Sahel savanna AEZ (Table S1), the soils are deep sandy with high average sand content (> 84%) except the silty and more acidic soil at Tchoukoulawa. Saturated hydraulic conductivity varied from 3.5 to 14 m hr^{-1}. The OC, total N and available P contents were very low varying from 0.3 to 2.4 g kg^{-1}; 0.1 to 0.3 g kg^{-1}; 0.5 to 2.8 mg kg^{-1}, respectively. In the Sudan-Sahel AEZ (Table S2), the soils are deep and have average sand content greater than 82% at few of the locations. The soils at two of the sites are silty (12–32% silt) throughout profile and clayey from 40 cm depth. The OC, total N and available P contents are very low varying from 1.35 to 3.16 g kg^{-1}; 0.13 to 0.26 g kg^{-1}; and 0.76 to 8.5 mg kg^{-1}, respectively. The soils also varied in their properties in the Sudan savanna AEZ (Table S3). The soils at two of the sites (Yakoye Tounga and Guitodo) are shallow and predominantly sandy loam in texture. Soil pH is acidic (4.1–4.5) at Guitodo and Goumandey Kouara but slightly acidic (5.9–6.5) at the other sites.

Seasonal analysis

After model calibration and evaluation, long-term simulations (1984–2020) were performed across the 18 selected sites using the DSSAT CERES-Millet Model. The simulation sites are Aitadan, Dandoukou, Dabala, Elkolta, Hardo Bara and Toukoulawa (Sahel savanna AEZ); Fabirdji, Garin Bando, Gazawa, Gotheye, Guidan Habou and Tajae (Sudan-Sahel AEZ); Falmey, Yakoye Tounga, Goumandey Koira, Guitodo, Koutoumbou, and Tara (Sudan savanna AEZ). The agro-ecological conditions in the selected sites were representative of those in the main millet production area in Niger. The seasonal analysis was carried out to test the effects of

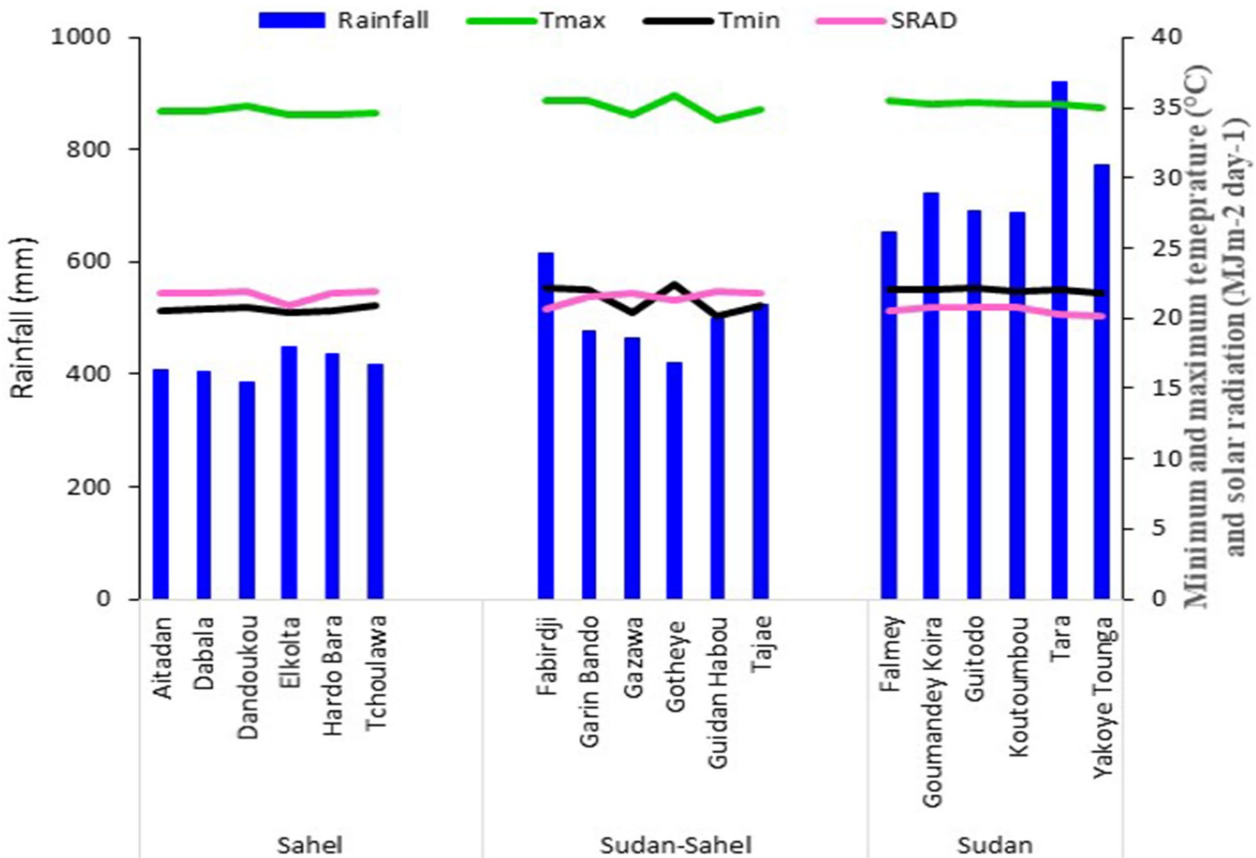

Fig. 2 Thirty-seven years (1984–2020) average rainfall, minimum and maximum temperatures of the 20 study sites in Sahel, Sahel-Sudan and Sudan AEZs of Niger Republic

plant density and nitrogen application rate on grain yield. Three millet varieties (CHAKTI, HKP, and SOSAT-C88) with different characteristics were compared. In the three agro-ecological zones, the sowing date was June 30 for all years of simulation. The sowing was set at a soil depth of 5 cm. The treatment included five different plant densities (1.5, 3, 6, 9, and 12 plants m^{-2} corresponding to 15,000; 30,000; 60,000; 90,000 and 120,000 plants ha^{-1}, respectively) with four levels of nitrogen (0, 20, 40, and 60 kg N ha^{-1}). For the N rates, half of the N was applied as per treatment at 14 days after sowing, while a second N application was set at 42 days after sowing. The phosphorus and potassium (K) were assumed to be non-limiting; therefore, the P and K sub-models were turned off. The model was set to harvest when the crop reached maturity. For the seasonal analyses, soil data from Sudan savanna, Sudan-Sahel, and the Sahel savanna zones were used (Tables S1–3). The soil and weather data were inputted, respectively, into the 'SBuild' and 'Weatherman' utilities software on the DSSAT v4.8 for the analysis. The 36 years simulations are initiated at planting; each year's simulation is independent of the previous year. This was done to evaluate the sensitivity of the treatment based on the annual rainfall variability, not the residual effects of the previous treatment.

Data analysis

Because the simulation was tested across different location within each AEZs, we determined the relative contribution of different management and environmental factors on the total simulated grain yield variance using a global sensitivity analysis for each entire simulation result using the procedure described in Monad et al. (2006). Two sensitivity indices were calculated: main effect (ME) which determine the relative contribution of a given factor to the overall yield variance including residuals (Eq. 4). The total effects (TxE) sensitivity index estimated the total contribution of a given factor together with other factors (Eq. 5). These indices were determined to assess variable of importance contributing the most to the yield variance based on Monte Carlo uniform inputs (Saltelli 2002).

$$ME_i = \frac{Variance(E[YieldX_i])}{Variance(Y)} \quad (4)$$

$$TxE_i = 1 - \frac{Variance(E[YieldX\_i])}{Variance(Y)} \quad (5)$$

where, is $E[YieldX_i]$ is the expected crop across all factors (X_i); $E[YieldX\_i]$ is the shared expected grain yield of all factors except X_i. The factors considered where variety, location, density, and year. We found the location explained < 10% of the simulated grain yield variance, thus subsequent analysis were averaged across all locations with a AEZ (Figure S1).

To determine whether the simulated yields differed depending on millet varieties, N, and density rate and AEZ, linear mixed-effects (LME) models were fitted with the grain yield as response variable. The main effects of variety, N rate, plant density, and their interactions on simulated millet grain yield were considered as fixed effects, while year nested within location was fitted as a random term in the models separately for each AEZ. The LME model was fitted using "nlme" package (Pinheiro et al. 2021) in R 4.3 implemented in RStudio v 2023.9.1.494 (Posit Team 2023). Means separation was conducted using the Tukey HSD test based on estimated marginal means using the "emmeans" package v.1.8.8 (Lenth 2023).

Millet production risk was assessed at each AEZ using cumulative probability distribution graphs. The acceptable grain yield required to compensate for the minimum production cost of millet in Niger was set to 975 kg ha^{-1} (75th percentile of the simulated data). Yield below this threshold across variety × density × N rate combination space was considered a risk. This grain yield threshold compensated the minimum operational costs of millet production in the Niger conventional management practice (60,250 Franc CFA ha^{-1}; Nourou et al. 2020). All figures were produced using the "ggplot2" package (Wickham 2016).

Results

CERES-millet model calibration and evaluation

Model calibration

The results of the model calibration for the three millet varieties across 2 sites are presented in Fig. 3. All the three varieties showed RMSE values of less than one day for days to flowering and maturity. The d-index values for CHAKTI, HKP, and SOSAT are 0.5, 0.69, and 0.78, respectively for flowering, and corresponding d-index values for physiological maturity are 0.5, 0.70, and 0.78 for the varieties (Figs. 3a, b). The calibration results also indicated that the model was generally able to simulate grain yield very well for all varieties. There was good agreement between the observed and simulated data for grain yield, as indicated by a low RMSE ranging from 12.6 to 70.3 kg ha^{-1}, high d-index ranging from 0.78 to 0.95 for all varieties (Fig. 3c).

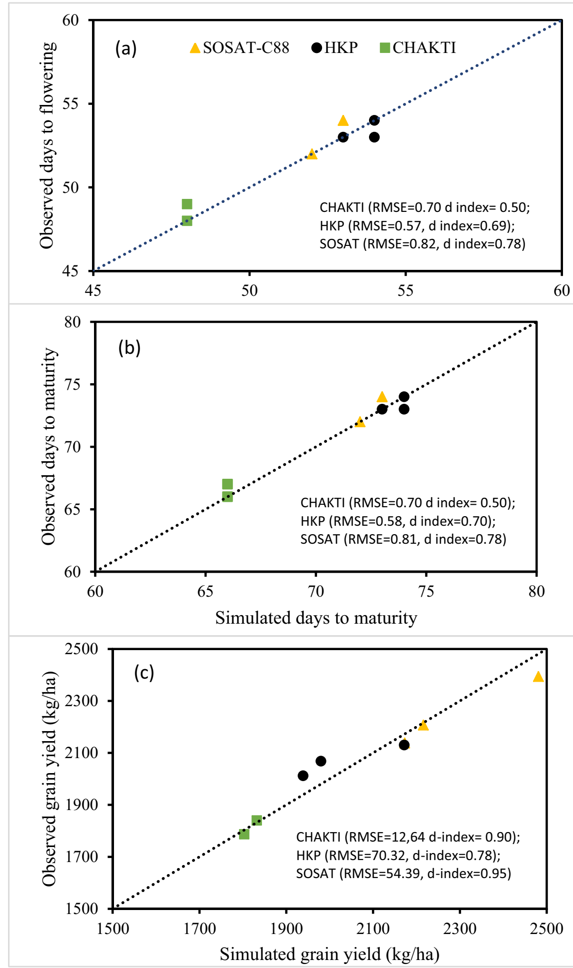

Fig. 3 Observed vs simulated days to flowering (**a**), days to maturity (**b**) and grain yield (**c**) using calibration experiment in Niger Republic

Model evaluation

For model evaluation using the independent data sets (Figs. 4a–c), there were good agreements between observed and simulated values for phenological parameters and yield as shown by the model statistics. The model evaluation results for simulated days to flowering and maturity were in close agreement with the observed data. Low RMSEs of 1.7 to 3.0 days for flowering and 1.5 to 3.0 days for maturity were obtained for the three varieties (Figs. 4a, b). The evaluation of grain yield for the three varieties demonstrated a strong agreement between the simulated and observed data, with low RMSE below 100 kg ha^{-1} for all varieties. All the varieties recorded d-index values > 0.7 for all measured parameters (Fig. 4c).

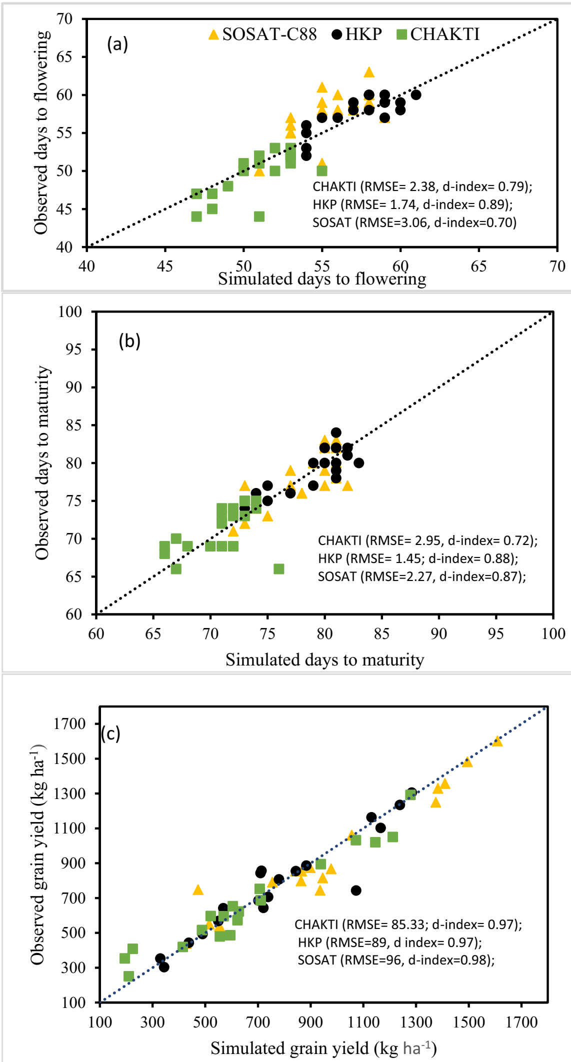

Fig. 4 Observed vs simulated days to flowering (**a**), days to maturity (**b**) and grain yield (**c**) using evaluation experiment in Niger Republic

Seasonal analysis

Impact of planting density and nitrogen application

Seasonal analysis showed that grain yield increased with increasing nitrogen rates for all planting densities (Fig. 5). However, grain yields were consistently less than 600 kg ha^{-1} under 0 kg N ha^{-1} rate irrespective of plant density, variety and AEZ. SOSAT was the most responsive variety to N application and plant density in all AEZs. The simulated grain yields were consistently higher in Sudan-Sahel and lowest in Sahel across all N and density rates. All the varieties did not respond significantly to changes in plant density beyond 6 plants m^{-2}. Response to N was higher for the medium-maturing HKP and SOSAT than for the early maturing CHAKTI.

The Sudan AEZ was the most responsive to N application with grain yields increasing from 64 to 1154 kg ha^{-1} when N application changed from 0 to 60 kg N ha^{-1} (Fig. 5). The simulated grain yield was also significantly influenced by plant density and was lowest at 1.5 plants m^{-2}. In Sahel AEZ, simulated yields did not significantly differ when plant density increased from 3–12 plants m^{-2} (Fig. 6, Table S4). However, in Sudan AEZ, yield was lowest at 1.5 and 12 plants m^{-2} and maximum at 6 plants m^{-2} (Fig. 7). In the Sudan-Sahel AEZ, simulated yield differs significantly and was predicted to increase from 492 kg ha^{-1} to > 700 kg ha^{-1} when plant density increased from 1.5 to above 6 plants m^{-2} (Fig. 8).

Across all AEZs, grain yield of the variety CHAKTI was comparatively lower than that of HKP and SOSAT (< 1000 kg ha^{-1}) irrespective of planting density and nitrogen application. In Sahel AEZ, the grain yields of CHAKTI were statistically similar at both 1.5 and 3 plants m^{-2} at moderate N rate (20 kg N ha^{-1}). Grain yield, however, increased by 27–46% with increasing planting density to 6 plants m^{-2} beyond which there was no further significant response at all N rates (Fig. 6). Grain yield of CHAKTI was more responsive to N application and plant density variation in the Sudan AEZ (Fig. 7). There was increase in grain yield with increasing N rate up to 40 kg ha^{-1}. Increasing N rate from 40 to 60 kg N ha^{-1} led to less than 300 kg ha^{-1} increase in grain yield at plant density of 3 plants m^{-2}. The grain yields of CHAKTI in Sudan AEZ was maximized at 6 plants m^{-2} and there was decrease in grain yield with increasing plant density beyond 6 plants m^{-2}. A different trend was observed in Sudan-Sahel AEZ where there was linear increase in grain yield with increasing N rate at plant density greater than 3 plants m^{-2}. And yield was higher at higher N rate and plant density (Fig. 8).

There was strong response of HKP to N application and plant density in all the AEZs (Figs. 6, 7 and 8). Generally, grain yield increased (23–44%) with increasing planting density to 6 plants m^{-2}, beyond which there was no significant increase in the Sahel savanna AEZ (Fig. 6). The mean simulated grain yield of HKP in Sudan AEZ was significantly higher at 60 kg N ha^{-1} with yield increasing by nearly 2-folds when N rate increases from 20 to 40 kg N ha^{-1} irrespective of plant density. In the Sudan-Sahel AEZ, there was lower increase in grain yield of HKP with increasing N rate compared to Sudan AEZ. However, the overall yield dynamics were similar with grain yield consistently higher at high N rate and plant density (Figs. 8, 9).

Both main and interaction effects of N rate, plant density and cultivar were significant for SOSAT in all the three AEZs (Table S4). Grain yield of SOSAT significantly increase with increasing N application rate and plant density. The grain yield was consistently lower in Sahel followed by Sudan-Sahel and Sudan AEZ. In Sahel and

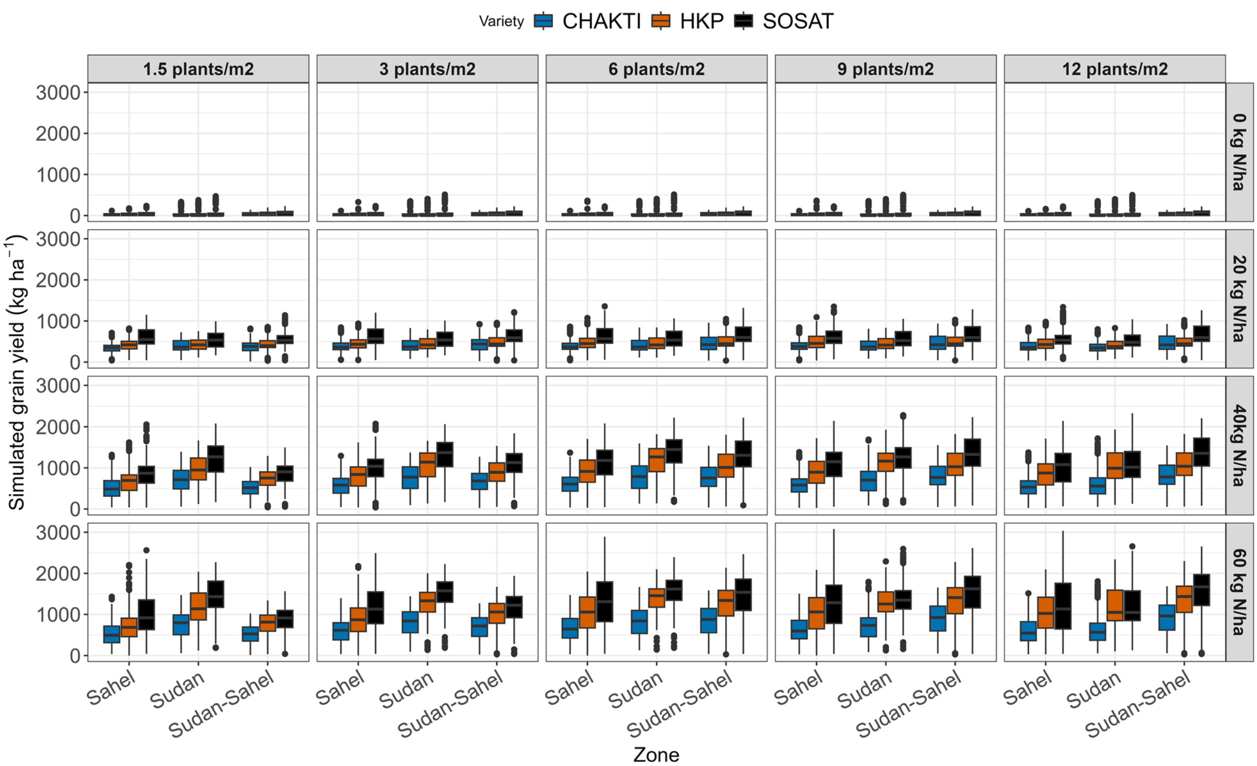

Fig. 5 Distribution of the simulated grain yield the three millet varieties under different level of nitrogen and plant density during the last 36 years (1984–2020) across the three AEZs of Niger Republic. Boxplots show the median (solid line), the 25th and 75th percentile (solid box) and 5th and 95th percentile (whiskers)

Sudan AEZs, grain yield of SOSAT was maximized at 6 plants m^{-2} and 60 kg N ha^{-1}. In the Sahel-Sudan AEZ, maximum grain yields were simulated at 12 plants m^{-2} for SOSAT (Figs. 8, 9).

Production risk analysis

Millet production risk was assessed at the sites in the three agroecological zones using the cumulative probability distribution graphs (Fig. 10). The acceptable grain yield required to compensate for the minimum production cost of millet in Niger was set to 975 kg ha^{-1} (75th percentile of the simulated data). Yield below this threshold across variety × density × N rate combination space was considered a risk. Thus, the acceptable yield threshold that must be met or exceeded was set at ≥ 975 kg ha^{-1} for all varieties, plant density, and AEZs. This threshold was never achieved under 0 kg N ha^{-1} application irrespective of variety and AEZ. At 20 kg N ha^{-1} application, SOSAT achieved this threshold in 25% of the simulation years when plant density exceeds 3 plants m^{-2} in Sudan-Sahel, and Sahel. Thus, SOSAT had the highest stability and lowest downside risk irrespective of N rate or plant density across all AEZs (Fig. 10). CHAKTI and HKP had the highest production risks under these scenarios. Increasing N application from 20 to 40 kg N ha^{-1} mitigate these risks where grain yield was above this threshold for all varieties in more than 50% of the years under all plant densities except in Sahel where this threshold was only achieved in < 20% of the years. In all AEZs, increasing plant density above 6 plants m^{-2} increases this risk under low to moderate N application, but the yield was mitigated when N was applied at high rates (Fig. 10). Consistent across AEZs, CHAKTI carried the highest downside risks irrespective of N rate and plant density.

Discussion

Pearl millet is an important food security crop in the West African Sahelian region and particularly in Niger. Yields are however, low due to several biotic and abiotic constraints (Akponikpè et al. 2008). Several millet varieties along with crop management technologies have been identified to improve yields of millet on farmers' fields in Niger. Long term evaluation of these technologies in multiple locations, however, would require combining results from short-term experiments on crop management interactions with validated crop models to give more spatial coverage and make better technology and location specific recommendations (Silungwe et al. 2019; Tovihoudji

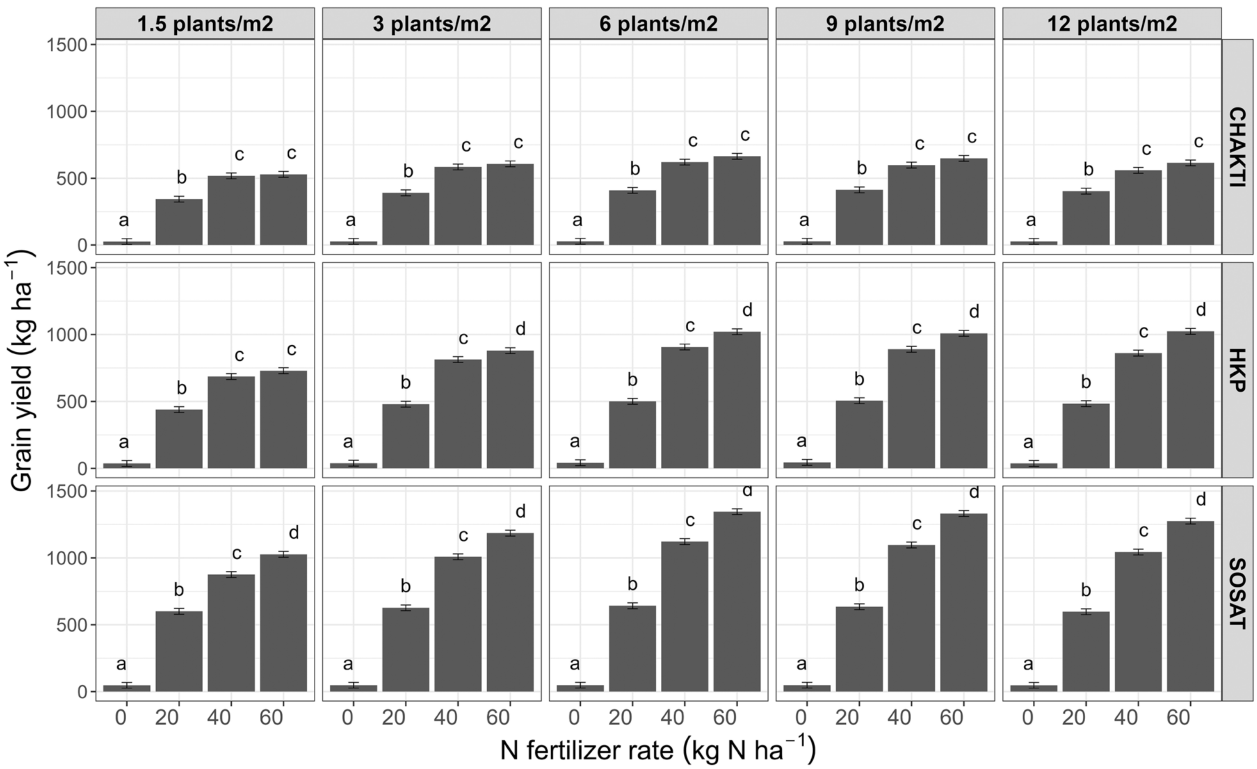

Fig. 6 Effects of plant density (top panel) and N rate (bottom panel) of three millet varieties (vertical panel) on simulated grain yields in Sahel AEZ of Niger Republic. Error bars are standard error (±) of the mean. Within each panel, mean values labeled with the same letter were not significantly different at $p < 0.05$ (Tukey's HSD)

et al. 2019). In this study, we calibrated and validated the DSSAT CERES-Millet model for days to flowering, days to physiological maturity and grain yield (Figs. 3, 4) for three millet varieties in Niger and used the results for long term simulation of millet yield for response to planting density and nitrogen application. Results of calibration and validation show that the model accurately reproduced the observed values for days to flowering, days to maturity and grain yield consistent with the findings of Mohamed et al (2022) and Soler et al (2008) who obtained similar results for millet in Niger.

Seasonal analysis across agroecological zones

The long-term simulation results show that millet performance depended on variety, AEZs, sites within AEZs, N application rate and planting density. Millet yields were higher in the Sudan (7–285%) and Sudan-Sahel (3–220%) than in the Sahel savanna AEZ because of higher rainfall and better soil fertility in these zones. Kamara et al. (2023) reported that maize yields were lower in the Sahel than in the Sudan and Sudan-Sahel AEZ of Niger because while rainfall varies from 706 to 792 mm in the Sudan savanna and 445–540 mm in Sudan Sahel, rainfall in the Sahel is mostly below 400 mm. The soils in the Sahel savanna AEZ are also poorer in fertility with very high sand (above 80%) content compared to the other zones (Table S1). This limits the ability of the soil to retain water and nutrients (Akponikpè et al. 2014).

Simulated yield significantly differed among the three varieties in all the AEZs. The early-maturing variety CHAKTI produced the least yields (690–883 kg ha^{-1}) in all AEZs at all planting densities and N rates. The performance of the widely cultivated variety HKP was also good, yielding more than 1000 kg ha^{-1} at N application rates of 40 and 60 kg ha^{-1} and plant densities above 1.5 plants m^{-2}. Under rainfed conditions in Niger, CHAKTI matures in 66 days after planting while HKP matures in 73 days and SOSAT matures in 75 days. Early maturing varieties usually accumulate less dry matter and therefore produce less grain yield (Liu et al. 2023). Increase in plant density did not confer yield advantage to the early maturing variety as there was no interaction between variety and plant density. The simulated yields of the medium-maturing variety SOSAT was consistently higher than those HKP and CHAKTI in all AEZs. Wilson et al. (2008) reported SOSAT–C88 among the downy mildew (caused by *Sclerospora graminicola* (Sacc.) Schroet.) resistant entries tested across location and years in Sub Saharan

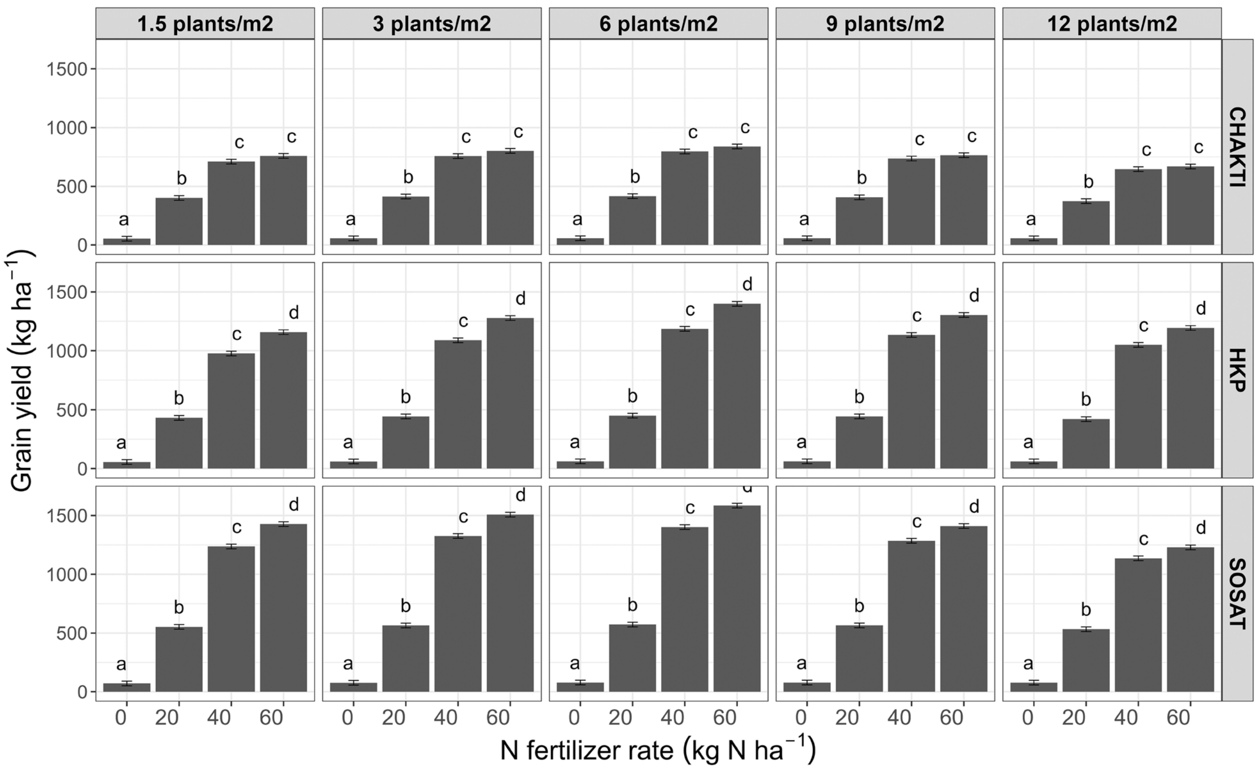

Fig. 7 Effects of plant density (top panel) and N rate (bottom panel) of three millet varieties (vertical panel) on simulated grain yields in Sudan AEZ of Niger Republic. Error bars are standard error (±) of the mean. Within each panel, mean values labeled with the same letter were not significantly different at $p < 0.05$ (Tukey's HSD)

Africa. Thus, its resistance and adaptability to the dry regions of Niger confers advantage to produce significantly higher yields in favourable environments.

Grain yields of the three varieties consistently increased with increasing plant density up to 6 plants m^{-2} for all varieties in all AEZs. This is far above the nationally recommended planting density of 3 plants m^{-2}. This suggests that there is room for improvement in the recommended density for millet in Niger. There is, however, no significant response to increases in plant density at N rates below 40 kg N ha^{-1} in most locations. It should be noted that, though significantly high yields were simulated at plant populations of 6 plants m^{-2}, yields at the low planting density of 3 plants m^{-2} were more stable as the grain yield was consistently below 1000 kg ha^{-1} in 90% of the years. The variability at high plant densities may be due to the insufficient rainfall in some of the years of simulation. Alhassane et al. (2008) reported enhanced leaf area development under all planting densities of ZATIB millet variety. However, under water deficit, the high planting density had a negative impact on plants having received urea suggesting that the use of high rates of urea was conceivable only with low planting densities in zones with erratic rainfall such as the Sahel. Significantly high yields (> 1000 kg ha^{-1}) were, however, simulated for plant densities above 1.5 plants m^{-2} for HKP in the Sudan Sahel and for SOSAT in the Sudan savanna AEZ. In Senegal, Faye et al. (2023) reported grain yield increased of millet varieties from 1000 kg ha^{-1} to 1600 kg ha^{-1} when planting density was increased from 12,500 to 25,000 seed hills ha^{-1}.

In the Sudan-Sahel and Sudan savanna AEZs, the CHAKTI variety did not significantly respond to N application beyond 40 kg N ha^{-1} for all plant densities. The low response of CHAKTI may be attributed to its earliness which may cause less demand for N. Other factors such as the poor soil fertility (< 2.0 g kg^{-1} OC and < 4.0 mg kg^{-1} P content) could have also contributed to this limited yield response of this variety in the very dry years and low high densities. The response of for HKP and SOSAT to high N rate (40 and 60 kg ha^{-1}) and to plant density was dependent on agroecology. In the Sahel savanna AEZ, there was no significant response to N beyond 40 N kg ha^{-1}. In the Sudan-Sahel AEZ, the response to N at the rate of 60 kg N ha^{-1} was significant for HKP and SOSAT. In the Sudan savanna AEZ, response to N application at 60 kg N ha^{-1} was also significant for HKP and SOSAT. Response to N

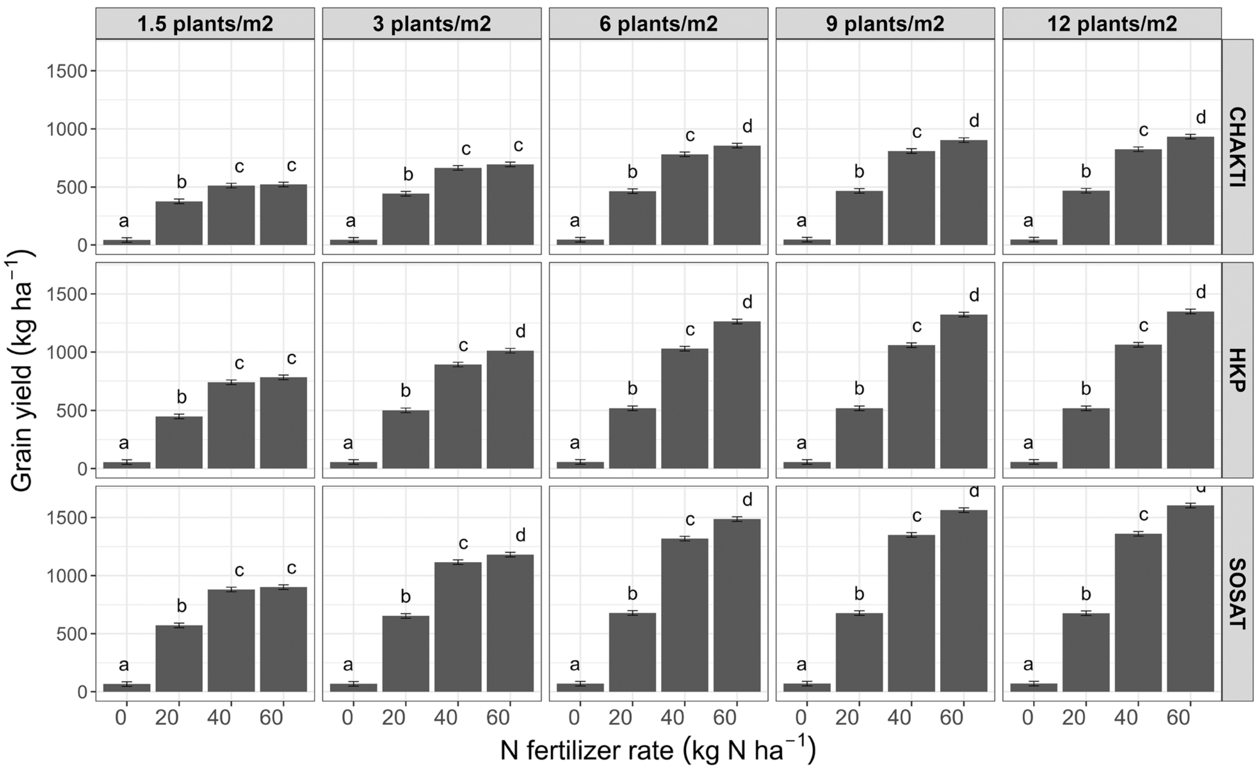

Fig. 8 Effects of plant density (top panel) and N rate (bottom panel) of three millet varieties (vertical panel) on simulated grain yields in Sudan-Sahel AEZ of Niger Republic. Error bars are standard error (±) of the mean. Within each panel, mean values labeled with the same letter were not significantly different at $p < 0.05$ (Tukey's HSD)

was generally low at low plant densities for all varieties with response increasing with increasing plant densities. Our results corroborate the findings of Pilloni et al. (2022) who reported significant yield increase in millet genotypes tested under high evaporative demand conditions and therefore confirmed a strong environmental effect on the response to density. Significantly low yields (< 500 kg ha^{-1}) were simulated at N rates below 40 kg N ha^{-1} for all the varieties in all the AEZs. This is contrary to findings of Akponike et al. (2010) who using the APSIM model showed that moderate N application (15 kg N ha^{-1}) improves both the long-term average and the minimum yearly guaranteed yield of millet in Niger. In an on-farm field study in the Sahel savanna of Niger, De Rouw (2004) reported that average of unfertilised grain yields was low for Sahelian farmers' fields: (331 kg ha^{-1} in manured fields, 248 kg ha^{-1} in long fallow fields, and 124 kg ha^{-1} in short fallow fields). She demonstrated a significant improvement of yield due to inorganic fertilisation in all cropping systems which is consistent with our simulation results. In a study by Araya et al. (2022), simulation results showed that N fertilization, greatly affected sorghum and millet yield, which can be considered as suitable crop management options to reduce risks under the projected mid-century climate in Senegal.

Risk analysis

The acceptable grain yield required to compensate for the minimum production cost of millet in Niger was set to 975 kg ha^{-1} (75th percentile of the simulated dataset). Thus, the acceptable yield threshold that must be met or exceeded was set at ≥ 975 kg ha^{-1} for all varieties, plant density, and AEZs. The probability of attaining the desired yield of ≥ 975 kg ha^{-1}, was generally low and generally less than 70% of the years in the Sahel Savanna AEZ for CHAKTI. Similarly, the probability of achieving this desired yield was less than 70% at all N rates and plant densities for HKP and SOSAT-88. This suggests that the yield potential of these varieties is low in the Sahel savanna AEZ. Kamara et al. (2023) reported very low chances of achieving optimal yield of early-maturing maize varieties in the Sahel savanna AEZ due to low and erratic rainfall and poor soils. In the Sudan-Sahel AEZ, the chances of achieving desired yields were dependent on-site characteristics for all varieties. For example, the probability of achieving the desired yield of CHAKTI occurs in 15–40% of the years for N rates above

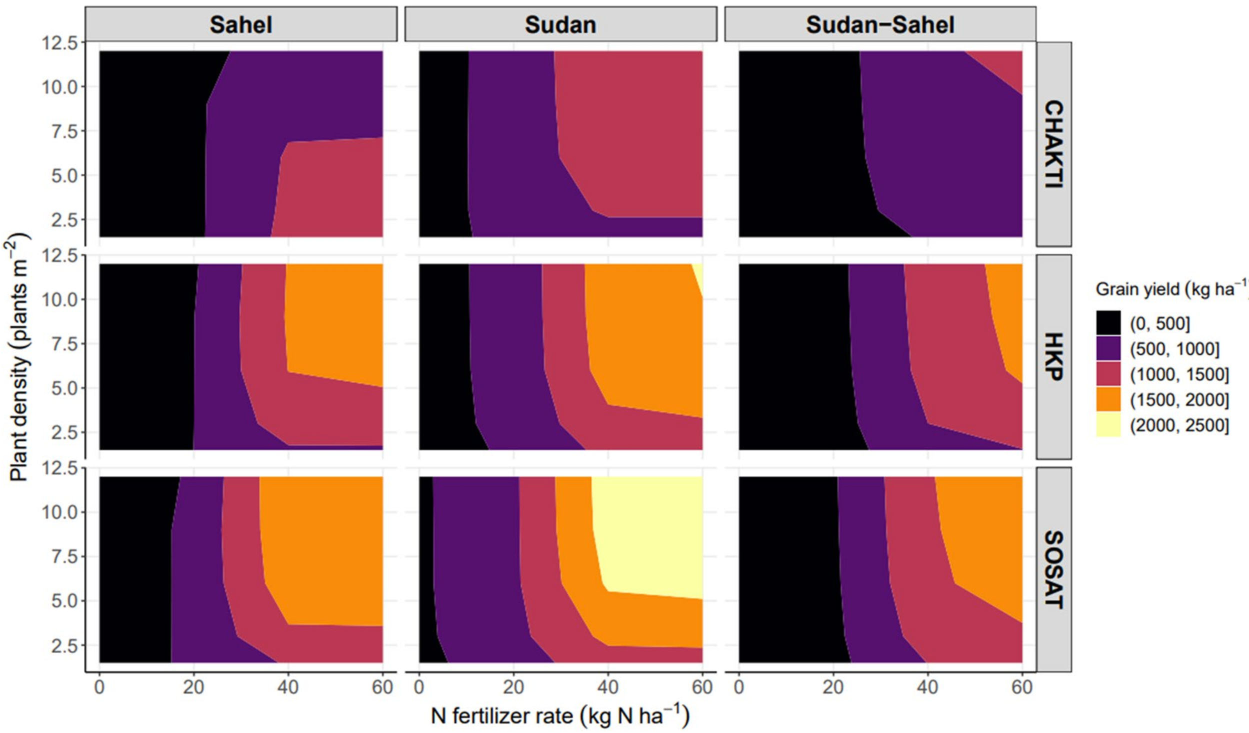

Fig. 9 Three-dimensional contour map illustrating the interaction of N rate × density × variety on millet grain yield across three AEZs in Niger Republic

40 kg N ha^{-1} irrespective of plant densities. In addition to site characteristics, the probability of achieving the desired yield was dependent on planting density for HKP and SOSAT. There were higher chances of achieving the desired yield at high plant densities at both 40 and 60 kg N ha^{-1} for these varieties. For example, the probability of achieving the desired yields will be 65–78% for HKP in 51–89% of the years for SOSAT at plant density of 6 plants m^{-2}.

In the Sudan savanna AEZ, the probability of attaining the desired yield will be below 70% for CHAKTI at all plant densities and N rates. The probability of achieving the desired yield was high (60–90% of the years) for HKP and SOSAT at all plant densities in the Sudan savanna AEZ suggesting that there is less risk of cultivating these varieties in this AEZ. De Rouw (2004) reported the conventional low-density planting did not produce high yields as frequently as higher densities under favorable conditions in Niger which is consistent with our findings. The author however, reported that there was less crop failure under harsh conditions with low density farming, although lower average grain yields were realized. Contrary to this assertion, our simulation results show that the desired yield thresholds would not be achieved at low plant densities and without N or with minimal application of N in all the three AEZs. Moreover, the desired yield will not be achieved for all the varieties with N application below 40 kg ha^{-1} except in Sudan-Sahel AEZ.

The long-term simulation results show that the application of N fertilizer alone may not increase response of millet to N. Moreover, the risk of not achieving the desired yield was still high in Sahel and Sudan AEZ even with the application of N. This shows that the use of integrated soil fertility management practices is necessary in the Sudano-Sahelian zones of Niger. This would involve the use of resilient varieties, application of inorganic fertilizer, organic manure, and use of soil conservation practices. Our study did not simulate the combined application of inorganic fertilizer, organic manure, and soil conservation practices. This is needed to provide information on the long-term benefits of integrated soil fertility management practices.

Conclusion

The CERES-millet model in DSSAT was calibrated and validated for use in simulating the response of three millet varieties to nitrogen application and plant density in three AEZ in Niger. The results show that the model accurately reproduced the observed values for phenology and grain yield of the three millet varieties used. The model can therefore be successfully used to simulate the performance of those varieties under

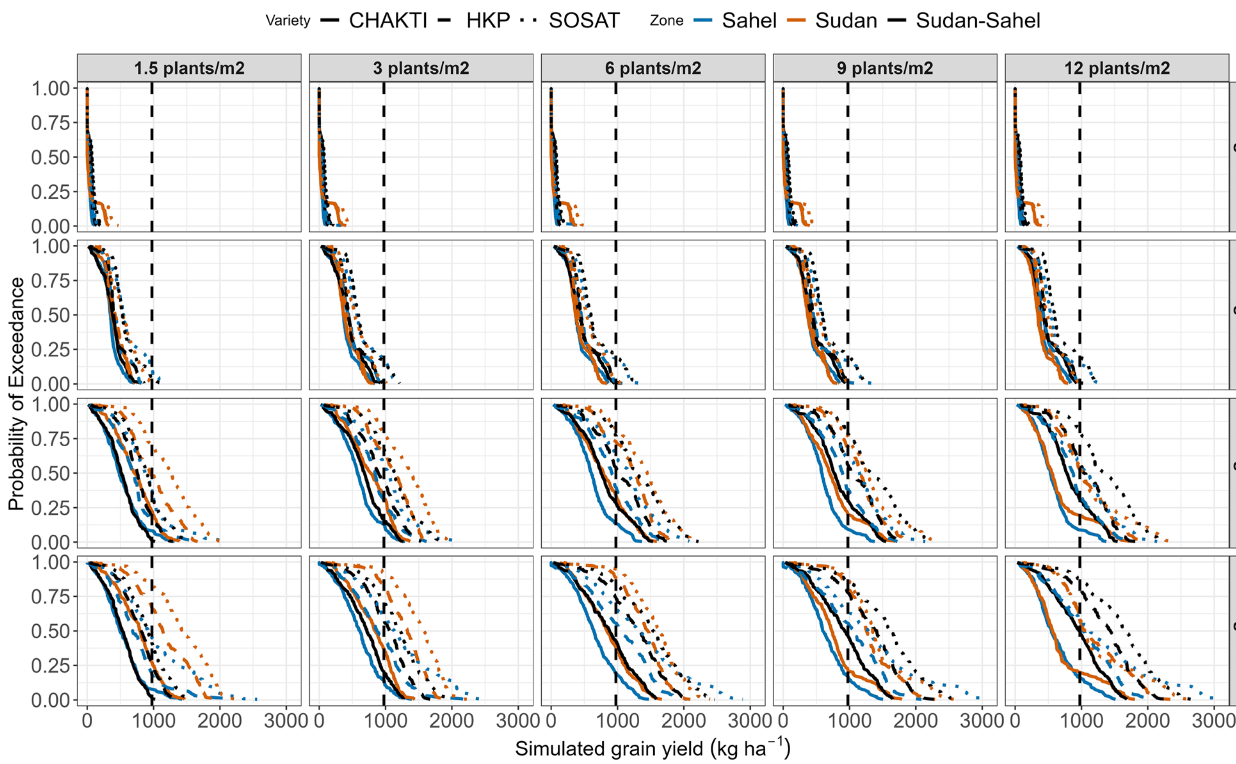

Fig. 10 Probability of exceedance plots showing the risk of grain yields being below a given value of the three millet cultivars across different plant density and N application rate at the three AEZs in Niger Republic. The probability of exceedance on the y-axis is a statistical metric describing the probability that a particular value on x-axis will be met or exceeded. The x-intercept (solid dash line) shows the grain yield at the 75th percentile of the entire simulated grain yield (975 kg ha^{-1}). this threshold is the acceptable grain yield required to compensated for the minimum production cost of millet in Niger. Yield below this threshold across variety × density × N rate combination space was considered a risk

varying crop management practices in the dry savannas of Niger. The 36-year simulation results showed that millet productivity is influenced by millet variety, agro-ecological zone, nitrogen application and planting density. The variety SOSAT was the most responsive to N application and plant density in all AEZs and the simulated yield of the early-maturing variety CHAKTI was significantly lower than those of the medium-maturing varieties (HKP and SOSAT). Consequently, under low N application (0 to 20 kg N ha^{-1}) and low to moderate plant density (1.5—6 plants m^{-2}), CHAKTI and HKP had the highest production risks. Increasing N application from 20 to 40 kg N ha^{-1} mitigate these risks where grain yield was above the 975 kg ha^{-1} threshold representing the minimum production cost for millet for all varieties in more than 50% of the years under all plant densities except in Sahel where this threshold was only achieved in < 20% of the years. In all AEZs, increasing plant density above 6 plants m^{-2} increases this risk under low to moderate N application, but the risk was mitigated when N was applied at high rates. Consistent across AEZs, CHAKTI carried the highest downside risks irrespective of N rate and plant density. This study demonstrated N application rate and plant density recommendations must be tailored to specific variety and AEZs to maximize grain yield and reduce volatility in Niger.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43170-024-00254-x.

Supplementary Material 1

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Author contributions
Maman Garba: Conceptualization, Methodology, Investigation, Data acquisition and curation, Writing—original draft and editing. Alpha Y. Kamara: Conceptualization, Methodology, Writing—review & editing, Supervision, Project administration, Funding acquisition, Ali M.L. Mohamed: Data acquisition, Methodology, Formal analysis, Writing—review & editing, Abdullahi I. Tofa: Conceptualization, Methodology, Data acquisition Methodology, Formal analysis, Writing—review & editing. Soulé A. Mahamane: Data acquisition, Formal analysis, Writing. Hanarou Salissou: Data acquisition and Formal analysis, Balkissa I. Kapran: Writing—Review & Editing. Tahirou Abdoulaye: Funding

acquisition, Project administration, Review. Ismail I Garba: Formal analysis, Methodology, Writing—review & editing.

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Data availability
Data will be made available on request.

Declarations

Competing interests
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.

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