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Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator

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ABSTRACT

The Agricultural Production Systems simulator (APSIM) model was calibrated and evaluated using two improved sorghum varieties conducted in an experiment designed in a randomized complete block, 2014–2016 at two research stations in Nigeria. The results show that the model replicated the observed yield accounting for yield differences and variations in phenological development between the two sorghum cultivars. For early-maturing cultivar (ICSV-400), the model indicated by low accuracy with root means square error (RMSE) for biomass and grain yields of 20.3% and 23.7%. Meanwhile, Improved-Deko (medium-maturing) cultivar shows the model was calibrated with low RMSE (11.1% for biomass and 13.9% for grain). Also, the model captured yield response to varying Nitrogen (N) fertilizer applications in the three agroecological zones simulated. The N-fertilizer increased simulated grain yield by 26–52% for ICSV-400 and 19–50% for Improved-Deko compared to unfertilized treatment in Sudano-Sahelian zone. The insignificant yield differences between N-fertilizer rates of 60 and 100 $kgha^{-1}$ suggests 60 $kgNha^{-1}$ as the optimal rate for Sudano-Sahelian zone. Similarly, grain yield increased by 23–57% for ICSV-400 and 19–59% for Improved Deko compared to unfertilized N-treatment while the optimal mean grain yield was simulated at 80 $kgNha^{-1}$ in the Sudan savanna zone. In the northern Guinea savanna, mean simulated grain yield increased by 8–20% for ICSV-400 and 12–23% for Improved-Deko when N-fertilizer was applied compared to unfertilized treatment. Optimum grain yield was obtained at 40 $kgha^{-1}$. Our study suggests a review of blanket recommended fertilizer rates across semi-arid environments for sorghum to maximize productivity and eliminate fertilizer losses, means of adaptation strategies to climate variability.

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APSIM; climate variability; N-fertilizer rate; rain-fed agriculture; water use efficiency

Introduction

In semi-arid Nigeria, sorghum [*Sorghum bicolor* (L.) Moench] production is regarded as a major cereal for food grain and fodder, predominantly grown under rainfed conditions [Guinea (800–1100 mm) to Sudan savanna (600–800 mm) zones (Marley et al. 2004; Mishra et al. 2008).

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In the drier Sahel (300–600 mm) environments, sorghum is also cultivated, but copes less than millet with the shortness of the rainy season. Its production has an important impacts on the country's food security, contributing directly to household food influencing their incomes due to its industrial demand (Ajeigbe et al. 2017). Sorghum displays a great diversity in growth, development and resource use efficiency and has the potential to improve productivity of resilient farming system. Water as an input and nitrogen nutrition of crops were two essential factors for crop productivity on which farmers can act directly in the short term (Lemaire, Charrier, and Hébert 1996). In the semi-arid region, the main constraint to crop production is insufficient of water supply during growth (Lai 1991). This occurs not because of a rain shortage alone, but also resulting in a loss of water through runoff and high evaporation (Zougmore et al. 2000; Fox and Rockstrom 2003). To improve water use efficiency for crop production, it, thus, requires increase of green water, which is defined as the fraction of rainwater that infiltrates into the rooted soil zone and that is used, through a process of transpiration for biomass production (Ringersma 2003). Sorghum has been found as water efficient crop transforming available water more into dry matter than most other C_4 crops (e.g., maize) (Dercas and Liakatas 2007) and the crop is able to utilize water as deep as 270 cm soil depth (Mishra, Thakur, and Singh 2015). Its production is not only limited by rain shortage and nitrogen nutrition, but by the poor resource base, low input use and returns and rapid population increases (MacCarthy et al. 2010; Ajeigbe et al. 2018a, 2018b).

Poor soils (Bationo et al. 2003; MacCarthy, Sommer, and Vlek 2009) and unfavorable rainfall conditions due to drought or low moisture availability in a largely water-limited semi-arid environment (Akinseye et al. 2017) are further results to low sorghum productivity. Although, sorghum is reported to respond to mineral fertilizer, especially nitrogen in the Nigeria savannas, farmers usually prefer to apply nitrogen to maize or rice crop. In additions, due to peculiar farming practice in the region, the levels of fertilizer input do not compensate for nutrient lost through crop harvest, thereby creating a negative nutrient balance (MacCarthy et al. 2010). However, Ajeigbe et al. (2018a, 2018b) have reported that the use of inorganic fertilizers increased growth and yield of sorghum by 29–90% at optimal rates of 60 and 80 kg N ha^{-1}, as well as improved the chemical properties of soil in a Sudanian zone of Nigeria. Similarly, MacCarthy et al. (2010) reported the use of mineral N fertilizer at optimal rates of 40 and 80 $kgNha^{-1}$ economically profitable while agronomic N use efficiency was found between 21 to 37 kg grain kg^{-1} N with intensively managed homestead fields. The information on sorghum response to mineral fertilizers is, however, localized (NAERLS 2014). This makes it impossible to extrapolate fertilizer recommendations to other areas in the semi-arid region of Nigeria where sorghum is an important crop. It is therefore imperative to explore nutrient and water productivity in the context of smallholder farming condition in order to make informed decisions. As the environment is also an important biophysical yield-limiting factor, nitrogen and water productivity were could be assessed under a wide range of weather conditions.

Systematic analysis of N responses and water productivity requires long term crop yield data sets. Experimental data are limited and expensive, as they require several years of data gathering. A better way to understand the dynamic processes of the effects of these on crops is by using Crop Models. The use of dynamic and well-tested crop growth models can be an effective way to analyze the complex interaction of environment and management on crop productivity. However, crop simulation models have proven to provide an excellent approach to explore genotype × environment × management interactions and adaptation research for agriculture (Porter et al. 2014; Chenu et al. 2017; Nendel et al. 2018). The Agricultural Production Systems sIMulator (APSIM) framework (Keating et al. 2003; Holzworth et al. 2014) is one of the cropping systems models that describe the dynamics of crop growth, soil, water, soil nutrients and plant residues as a function of climate, cropping history and soil/crop management in a daily time step. Through the linking of crop growth with soil processes, APSIM is particularly suited for the evaluation of likely impacts of management practices on the soil resource and crop productivity. The model has been used successfully in the search for strategies for more efficient production, improved risk management, crop adaptation and sustainable production (Keating et al. 2003; Van Ittersum, Howden, and Asseng 2003; Kisaka et al. 2015). APSIM-sorghum are widely calibrated against independent crop dataset for resource-constrained and risky environmental condition of semi-arid smallholder farming systems (Whitbread et al. 2010; Akinseye et al. 2017).

Several studies focused on a wide area of applications with the use of crop growth models. For example, Delve et al. (2009) reported the use of the APSIM model to aid decision making regarding N fertilization of pearl millet in the Sahelian region. It was found that model suitably predicted plant available water (PAW), simulated water and nitrogen stress were in agreement with measurement (water) and expectation (N) regarding the fertilizer and rainfall conditions of the experiment. MacCarthy et al. (2010) reported APSIM model to adequately predict the grain yield response of sorghum to both N and P applications when assessed the impact of contrasting nutrient and residue management practices on sorghum crop over semi-arid Ghana. Also, simulated P responses in annual crops on contrasting soil types using the APSIM model for maize and beans in Kenya was reported by Delve et al. (2009). The model adequately reproduced the observed grain yields of the two crops. The future climate risk on cereal crops for family food self-sufficiency over southern Mali was assessed by Traore et al. (2017) using APSIM. The study found that the food availability is expected to reduce for all farm types based on future climate and current farming practices while the large and medium-sized farms can still achieve food self-sufficiency if early planting and recommended rates of fertilizer are applied. Therefore, with the use of APSIM model, biomass and grain production as well as the water use of promising variety can be extrapolated. By applying a well-calibrated crop growth models, it would help to estimate their potential productivity across different sites and soil conditions, as well as addressing the impact of different management interventions such as fertilizer application input. With this background, this study seeks to simulate the long term response of sorghum to N-application and water productivity in the semi-arid region of Nigeria. This outcomes will guide the formulation of recommendations for better adaptations to climatic risk and fertilizer management for the smallholder farmers in the semi-arid.

Materials and methods

Study area and climatic condition

The study examined the response of sorghum to different N-fertilizer application and water productivity at three (3) selected sites within the semi-arid region of Nigeria. These sites are representative of three agro-ecological zones which include Sokoto [12.94°N, 5.23°E, 305 m above sea level (asl); Sudano-Sahelian zone], Kano (12.00°N, 8.59°E, 488 m asl; Sudan savannah zone) and Samaru [11.08°N, 7.72°E, 688.12 asl; Northern Guinea savannah zone]. The three sites were selected based on their differences in biophysical characteristics. The climatic conditions are typical of the southern edge of the Sahelian zone to Northern edge of Savannah, with rainfall marked mono-modal pattern and high temperature throughout the year (Akinseye et al. 2016). Rainy season starts between May and October. Depending on the onset date of major rains, sorghum locally planted from May to July. The long-term (1981–2016) mean annual rainfall of 582 mm for Sokoto; 784 mm for Kano; and 977 mm for Samaru. Daily long-term weather records from synoptic and agro-meteorological stations were obtained from the Nigerian Meteorological agency (NIMET) and compared with long-term climate records of international Institute for Tropical Agriculture (IITA). They data comprised daily rainfall, minimum and maximum air temperature while the solar radiation data were sourced from database for Climatology Resource for Agroclimatology, National Aeronautics and Space Administration (NASA) http://power.larc.nasa.gov/cgibin/giwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov).

Daily PET was calculated from these data using FAO guidelines (Allen et al. 1998). Also, rainfall variability for the selected sites was determined by calculating the coefficient of variation (CV) as the ratio of standard deviation to the mean annual rainfall in a given period. Further values such as cumulative rainfall on monthly, seasonal, annual, number of rain days, start of growing season, end of growing season and length of growing season were computed across the sites. The start and length of growing season characteristics were calculated according to appropriate definition reported by FDALR (1990). According to Ritchie (1988), the soils used were generally classified Sandy loam at Sokoto and Kano, Psammentic Paleustalf and Typic Plinthustalfs by the United States Department of Agriculture (USDA) soil Taxonomy, meanwhile Samaru was loamy soil, fine-Silty isohyperthermic by USDA soil Taxonomy.

Experimental data for model calibration and evaluation

The experiment used for the model calibration and evaluation of the APSIM-sorghum modules was collected from on-station sorghum field trial conducted from 2014 to 2016 at the Institute of agricultural research (IAR) station, Minjibir (Lat. 12.17° N, Long 8.65°E, 473 m asl) and Teaching and Research farm, Bayero University Kano (BUK) (Lat.11.98°N and Long 8.43°E, 508 m asl). The agronomic data such as dates of sowing, flowering and maturity), yield and final biomass for two (early- ICSV-400 and medium- Improved Deko) sorghum varieties were obtained from several field experiments conducted in the context of larger varietal characterization trials under integrated soil fertility management (Ajeigbe et al. 2018a, 2018b). The soil of the experimental sites (Minjibir and BUK) were characterized as slightly acid to neutral (pH 5.5–7), and was low in plant available nitrogen, phosphorus and calcium, had low organic carbon content (OC $\leq$ 1%). Sorghum was sown at various dates in the month of June and July, in a randomized block design and replicated four times. During the field trials Supplementary irrigation was applied when necessary to reduce the effect of water stress on the crop growth, and fertilizer were applied to achieve non-limiting conditions of plant nutrition and health. The plant density was 44,444 hills ha^{-1} (0.75 m between rows and 0.30 m between hills) was thinned to 2 plant per hill 10–14 days after planting (DAP). All plots had a planted border measuring one row.

The two sorghum varieties used are widely grown by farmers for their high market value across Northern Nigeria. ICSV400 is a high yielding, medium tall (1.8 to 2.1 m), photoperiod insensitive Guinea landrace that was developed from ICRISAT germplasm and formally released in 1996 for cultivation in Northern Nigeria. It is self-pollinating and flowers in 65 to 72 days, maturing in 100 to 110 days and producing grain yield of between 2.5 and 3.5 tha^{-1} under high fertility and good management . Similarly, the cultivar Improved Deko as it is locally called (12KNICSV-188) is a naturally bio-fortified variety with three times iron content than the typically grown sorghums (i.e., 129 ppm Fe compared to 40 ppm). Deko is a drought resistant variety with average yields of 2.4 to 2.8 t/ha, compared to the less than 1 ton per hectare from local varieties.

APSIM model overview and parameterization

APSIM is a widely used farming system model that simulates crop growth and development based on environmental variables (Holzworth et al.2014). For this study, five (5) in-built modules which include sorghum crop module (APSIM-sorghum), soil water module (SoilWat), soil nitrogen module (Soiln), residue module (Residue) and the manure module (Manure) were used accordingly. The sorghum module was calibrated and evaluated within the APSIM (APSIM v.7.9) framework for the two selected sorghum varieties grown under semi-arid conditions. The inputs data for model parameterization include crop management information, cultivar specific parameters (genetic coefficient), soil properties and daily weather records. As earlier described, the crop management and cultivar information for the two sorghum varieties were generated from the field experiments. Soil water dynamics between soil layers were defined by the cascading water balance method (Dalgliesh et al. 2016). Soil hydraulic characteristics in the model are specified by the drained upper limit (DUL), lower limit of plant extractable water (LL15) and saturated water content (SAT). Soil water content measurements before sowing defined the initial soil water content of the soil. Additional soil variables not available in the laboratory analyzed data were parameterized using APSIM soil protocol reported by Jones and Kiniry (1986). Also, the C:P ratio of roots and sorghum residues were calculated using measured field data. Climatic data used for both calibration and validation were obtained from automatic weather station installed within the experimental sites (<2 km radius) for the corresponding years include daily maximum and minimum temperature, solar radiation and rainfall. Management operations such as dates of all planting operations, sowing depth, plant density, type and amount of fertilizer, tillage (type, depth and fraction of above-ground materials incorporated) were properly setup. Genetic coefficients used by APSIM for sorghum are expressed in thermal degrees and photoperiod. Crop development is controlled by temperature (thermal degree days) and photoperiod. Thermal time accumulations were derived using algorithm described in Willmott et al. (1985) using observed phenology and weather data, a base temperature of 10 °C and an optimal temperature of 30 °C. Intercepted radiation and the radiation-use efficiency determined potential biomass growth of the crop in model. Meanwhile, water-limited growth is a function of water supply and the transpiration efficiency of the crop, which varies daily as a function of vapor pressure deficit. Temperature and N stresses defined the actual biomass increase, simulated from either potential or water-limited growth.

Evaluation of model performance

The performance of the APSIM model in predicting the days to 50% flowering, physiological maturity, grain yield and total biomass were evaluated using statistical indicators described below. Model evaluation entailed comparison of observed against simulated parameters based on growing seasons data obtained from the field experiment. The difference between the model simulated and field- observed data was adjusted by using trial-and-error approach where one particular variable was taken as the reference variable and subsequently adjusting the parameters which were supposed to clout the reference variable. Observed and simulated outputs were compared statistically using the root mean square error (RMSE) and normalized root mean square error ($RMSE_n$) computed according to Loague and Green (1991) and also Jamieson, Porter, and Wilson (1991) using Eqs. (1) and (2).

$$\text{R.M.S.E} = \frac{\sqrt{\sum_{i=1}^{n} (S_i - O_i)^{\ 2}}}{n} \tag{1}$$

Where: S_i represents the simulated, O_i represents the observed value, n represents the number of iteration taken into consideration.

The normalized root mean square error ($RMSE_n$) express in percent gives a measure (%) of the relative difference of simulated versus observed data.

$$\text{RMSE}n = \frac{\sqrt{\sum_{i=1}^{n} (S_i - O_i)^{\ 2}}}{n} \times \frac{100}{M} \tag{2}$$

where: P_i is the predicted value; O_i is the observed value; O is mean of the observed values; n is number of observation; and M is the mean of the observed variable. RMSE and $RMSE_n$ were calculated for biomass and grain yield. $RMSE_n$ gives a measure (in %) of the relative difference of simulated versus observed data. The simulation is considered excellent with $RMSE_n$ less than 10%, good if the $RMSE_n$ is between 10% and 20% fair if the $RMSE_n$ is between 20% and 30% and poor if the $RMSE_n$ is greater than 30% (Allen et al. 1998).

Table 1. Soil properties of the simulation sites for sorghum yield in the three (3) agro-ecological zones.

	Layer thickness (mm)				
Soil parameters	150	150	300	400	1000
Sokoto (Sudano-Sahelian zone)					
BD (gm^{-3})	1.30	1.33	1.38	1.44	1.50
SAT	0.384	0.384	0.385	0.385	0.384
LL ($cm\ cm^{-1}$)	0.103	0.117	0.131	0.130	0.119
DUL ($cm\ cm^{-1}$)	0.175	0.193	0.210	0.207	0.192
Organic C ($mg\ g^{-1}$)	0.84	0.67	0.41	0.23	0.12
Kano (Sudanian zone)					
BD (gm^{-3})	1.72	1.60	1.67	1.70	1.70
SAT	0.324	0.344	0.352	0.371	0.217
LL ($cm\ cm^{-1}$)	0.142	0.176	0.189	0.176	0.096
DUL ($cm\ cm^{-1}$)	0.241	0.28	0.294	0.282	0.271
Organic C ($mg\ g^{-1}$)	0.90	0.72	0.45	0.23	0.09
Samaru (Northern Guinea Savanna zone)					
BD (gm^{-3})	1.26	1.29	1.34	1.40	1.45
SAT	0.391	0.429	0.372	0.393	0.408
LL ($cm\ cm^{-1}$)	0.092	0.155	0.234	0.265	0.275
DUL ($cm\ cm^{-1}$)	0.239	0.285	0.353	0.381	0.395
Organic C ($g\ 100\,g^{-1}$)	1.38	1.06	0.68	0.40	0.22

Long term simulation of N-fertilizer applications on water use efficiency and yield productivity

After successful calibration and evaluation of the model for the two sorghum cultivars, a simulation was performed using long-term weather records (1981–2016). This was to analyze the potential sorghum productivity, including grain yield, water use and use efficiency, respectively. The simulations were carried out in three (3) representative sites, used for analysis of climate variability as described in the previous section. However, Table 1 displayed the three soils representing dominant soil types parameterized (Dalgliesh et al. 2016) for the three (3) agroecological zones in order to examine the effect of available water-holding capacity of the soil with site-specific rainfall characteristics and crop management. The soils used were mainly differ in texture and plant available water content (PAWC) as implies in each zone. The model initial water, nitrogen and organic matter contents were reset at the beginning of each simulation (first of April) to eliminate the residual effect of these parameter in the soil profile on crop growth and development for current season. Also, planting date for each season was controlled by a sowing rule module to aligned with the start of the rainy season and sorghum sowing window in each agroecological zone. This followed proven definition by Akinseye et al. (2016) which stated 20 mm of rainfall accumulates over 3 consecutive days. The planting rules represent current "best farmer's practice" for sorghum in the three agroecological zones. Thus, the simulation only reported key phenological development such as 50% flowering and physiological maturity, and also biomass and grain yield production. Water use efficiency was estimated according to site- and soil-specific evapotranspiration relative to grain yield (Probert et al. 1998). Therefore, potential evapotranspiration in the APSIM model was determined as described by Holzworth et al. (2014) and Probert et al. (1998). While WUE_{grain} were defined as the ratio of grain yield to water use (WU) between sowing and harvest was calculated from the model output.

Results and discussion

Rainfall and temperature variability in the selected agro-ecological zones

Across the selected agroecological zones, the rainfall pattern is mono-modal which comes with a short growing season (May–Oct). On the average more than 60% of rains was recorded in July

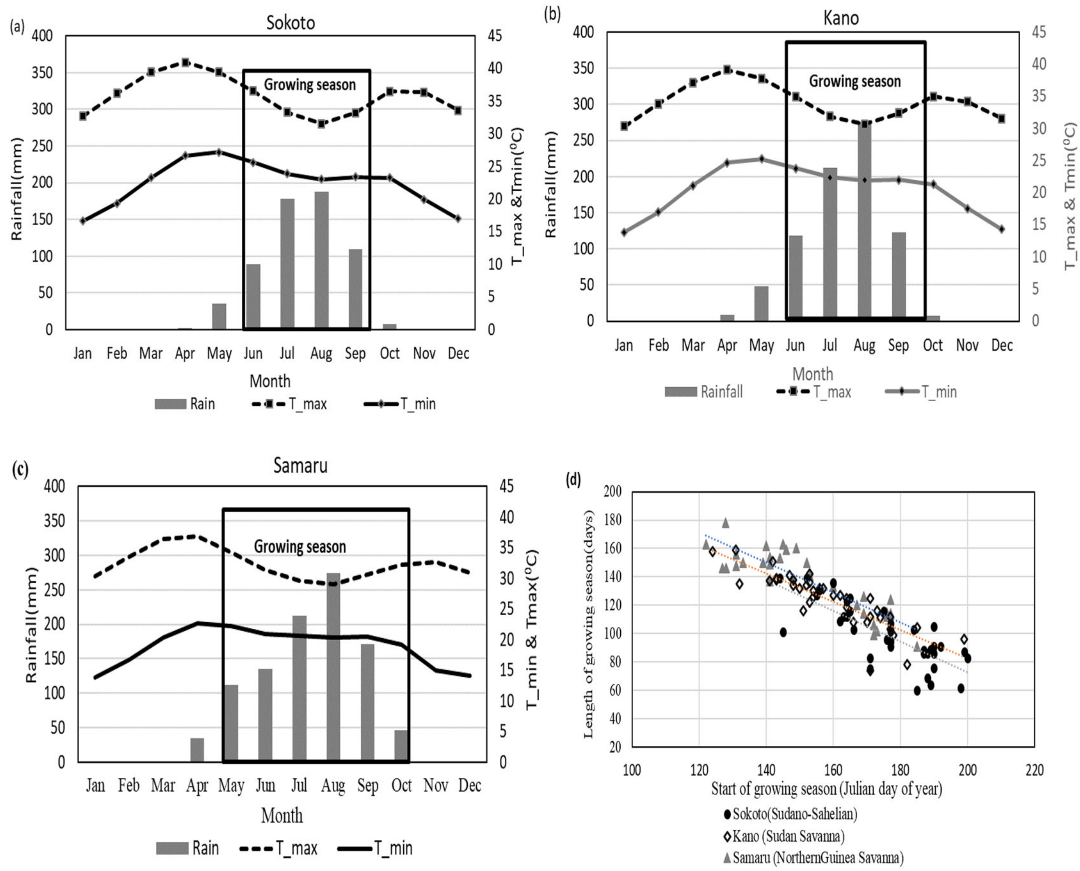

Figure 1. Monthly trend of rainfall, minimum temperature (T_min) and maximum temperature (T_max) as well as relationship between onset of growing season and length of growing season across the selected sites in three agroecological zones.

and August which implies the peak of rainy season across the selected sites (Figure 1a–c). For all the sites, mean monthly minimum and maximum temperatures show a significant warming trend throughout the growing season (Figure 1a–c). Minimum temperature (T_min) ranged from 23 to 27 °C in Sokoto; 21 to 25 °C in Kano and 19 to 22 °C in Samaru, respectively, while maximum temperature (T_max) varied from 31 to 39 °C in Sokoto, 31 to 38 °C in Kano and 29 to 34 °C in Samaru, respectively. However, the monthly and seasonal rainfall totals showed inherent variability which increases dis-proportionally as one moves from Sokoto (Sudano-Sahelian) to Samaru [Northern Guinea Savanna (NGS)] (Table 2). The lowest mean seasonal rainfall was recorded for Sokoto (583.4 mm), medium for Kano (785 mm) and the highest for Samaru (978 mm).

Notably, the results showed high coefficient of variation in rainfall amounts (CV-RA) during the months of May–June that signaled beginning of rainy season varied from 31.4 to 53.6% and also Sept–Oct which coincides the end of rainy season, varied from 32.4 to 94.4%. across the sites. Similar to amount of rainfall, coefficient of variation for rainy days (CV-RD) was higher in the month of May and October while the seasonal total of rainy days in Kano indicates mean highest of 73 days followed by Samaru (68 days) and Sokoto (65 days), respectively. The high CV-RA suggests high inter-annual variability in those months resulting to high level of uncertainty for crop establishment (May–June) and flowering/grain filling (Sept–Oct) during cropping season. This result is in agreement with the report by Araya and Stroosnijder (2011) that a coefficient of variation (CV) in monthly rainfall amount >30% indicated high variability both in RA and distribution trends. There was generally a strong negative correlation coefficient ($r = 0.8$) between the

Table 2. Variability analyses of monthly, seasonal rainfall amounts and number of rainy days in the study sites for simulation [Sokoto (1980–2016); Kano (1981–2017); Samaru (1983–2017)].

Parameters	May	Jun	Jul	Aug	Sep	Oct	Seasonal total
			Sokoto (Sudano-Sahelian zone)				
Rainfall amount (RA) in mm	35.6	89.0	178.1	187.4	109.8	10.8	610.6
Coefficient of variation in rainfall amounts (CV-RA) (%)	49.0	31.4	23.2	27.3	36.2	80.8	17.3
Rainy days (RD)	8	11	14	15	13	3	65
Coefficient of variation in Rainy days (CV-RD) (%)	35.4	24.0	15.4	22.1	22.6	71.8	11.3
Potential Evapotranspiration (ET_o)	6.49	5.94	5.05	4.47	4.93	5.48	5.39
			Kano (Sudan Savanna zone)				
Rainfall amount (RA) in mm	47.8	118.0	212.3	275.7	123.3	7.8	784.9
Coefficient of variation in rainfall amounts (CV-RA) (%)	53.6	32.8	17.0	24.7	32.4	81.4	16.1
Rainy days (RD)	10	14	17	17	12	3	73
Coefficient of variation in Rainy days (CV-RD) (%)	41.7	20.3	18.6	19.4	24.0	69.9	9.6
Potential Evapotranspiration (ET_o)	6.34	5.71	4.99	4.61	5.03	5.55	5.37
			Samaru (Northern Guinea Savanna zone)				
Rainfall amount (RA) in mm	112.3	134.7	213.0	274.7	170.7	46.2	977.6
Coefficient of variation in rainfall amounts (CV-RA) (%)	46.3	32.8	23.7	31.9	39.7	94.2	15.5
Rainy days (RD)	8	11	14	17	15	4	68
Coefficient of variation in Rainy days (CV-RD) (%)	34.2	16.8	17.7	17.3	19.8	69.5	9.8
Potential Evapotranspiration (ET_o)	5.48	4.83	4.30	4.02	4.53	4.94	5.04

onset and length of the growing season across the sites (Figure 1d). This suggests that an early onset of rains may probably translates to a longer growing season.

The onset of growing season (OGS) and length of the season (LGS) further revealed a high inter-annual variability for all the sites (Figure 2). The 25 and 75% percentile for OGS estimated the difference of 27 days at Samaru, 23 days at Kano and 22 days at Sokoto, respectively. For LGS, the results show that the cessation of rains remains more or less constant in most years in all three selected sites which implies that the delay in the start of seasons will results to shorter length for the growing period. LGS varied from 122 to 153 days at Samaru; 101 to 137 days at Kano; 85 to 113 days at Sokoto, respectively. This implies that sorghum variety longer than 120 days growing cycle may not be supported at Sokoto (Sudano-Sahelian zone) considering the high inter-seasonal variability of LGS and monthly rainfall distribution, as well as decreased number of rainy days. Similar results were reported by Rao and Okwach (2005) for enhancing productivity of water for legumes crop under variable climate. It was found that high inter-seasonal variability in the amount and distribution of rainfall, as well as decreased rainfall and increased temperatures in semi-arid Eastern Kenya.

However, the high level of degree of variability in the OGS and corresponding LGS could be attributed high degree of uncertainty for cropping activity planning which could be linked to risks of farming systems in semi-arid areas. The significant inter-seasonal variability affects both rainfall pattern and temperatures which can shift or even shorten traditional growing periods. Previously, studied by Recha, Kinyangi, and Omodi (2013); Akinseye et al. (2016) reported that determining the suitability of a cropping strategy in a certain area is a fundamental indicator of site-specific yield potential which could be mostly associated with the length and start of the growing period and its reliability to support early growth.

APSIM model calibration and evaluation

Table 3 depicts cultivar-specific parameters calibrated in APSIM which include thermal time from emergence to various developmental stages. The parameters for phenological development for ICSV-400 and Improved Deko cultivars were calibrated based on calculated thermal time for the observed phenological development stages. Base temperature, maximum grain number per head and grain growth rate were derived from observed biomass and grain production. For the

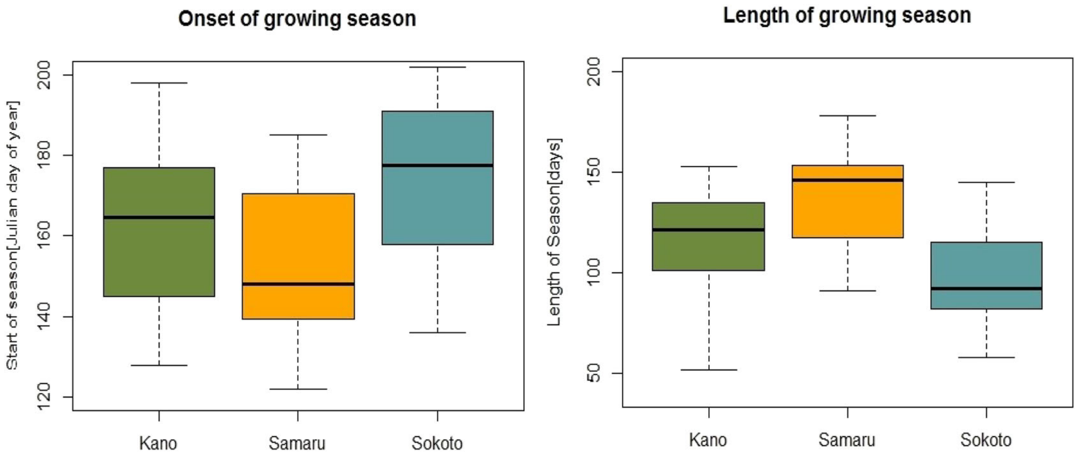

Figure 2. Boxplots representing characteristics of (a) onset of growing season (OGS) and (b) length of growing season (LGS) across the selected sites (Kano, Samaru and Sokoto).

Table 3. Cultivar- Specific parameters for ICSV-400 (early Maturing) and Improved Deko (medium maturing) used in APSIM-sorghum module simulation.

Parameters	Units	ICSV-400	Improved Deko	Remarks
Emergence-end juvenile	°C days	120	200	Calibrated
End juvenile-floral initiation	°C days	120	120	Calibrated
Flag leaf-flowering	°C days	170	170	Calibrated
Flowering-start grain filling	°C days	80	80	Calibrated
Flowering – maturity	°C days	500	550	Calibrated
Day length photoperiod to flowering	hours	12.8	12.8	Calibrated
Day length photoperiod for insensitivity	hours	13.2	13.2	Calibrated
Photoperiod slope	°C days	100	150	Calibrated
Growing deg day required to develop the most leaf ligules (leaf_app_rate_1)	°C days	53	53	Akinseye et al. (2017)
Growing deg day required to develop last leaf ligules (leaf_app_rate_2)	°C days	26.5	26.5	Akinseye et al. (2017)
Base temperature	°C	10	10	Akinseye et al. (2017)
Grain growth rate	g	0.00099	0.00088	Estimated
Maximum grain fill rate per head	mg/day	0.05	0.032	Estimated
Radiation use efficiency	g/MJ	1.65	1.35	Estimated
Transpiration use efficiency	kPa	0.009	0.009	Default

leaf appearance rate describing the most leaf and last leaf ligules as well as based temperature were based on published values by Akinseye et al. (2017). Results show that the calibrated cultivar-specific parameters accounts for yield potential, variation in growth characteristics and phenological development between the two sorghum cultivars. Thermal time from emergence to end of juvenile indicates 120 °Cdays for ICSV-400 and 200 °C days for Improved Deko. The

Table 4. Evaluation of the model performance for simulating phenological development, total biomass and grain yield for two sorghum cultivars calibrated under optimum condition.

				RMSE			
Cultivar parameters	Unit	*N*	MBE	Absolute value	% of mean observed	Observed range	Observed mean
ICSV-400							
50% Flowering	DAP	5	−2.8	3.3	6.7	67–71	68
Maturity	DAP	5	−0.5	4.4	4.7	92–96	94
Total Biomass	kg ha^{-1}	5	−296	1167	20.3	4105–7195	5740
Grain yield	kg ha^{-1}	5	28	364	23.7	1090–2088	1537
Improved Deko							
50% Flowering	DAP	5	−1.2	2.6	3.3	74–84	78
Maturity	DAP	5	1.6	3.3	3.1	100–111	107
Total Biomass	kg ha^{-1}	5	−1203	1362	11.2	10,184–14,656	12,296
Grain yield	kg ha^{-1}	5	232	353	13.9	1655–3060	2526

DAP: Days after planting; *N*: number of observations; MBE: mean bias error; RMSE: root mean square error.

results show that the model captured excellent with a very high accuracy for phenological development parameters. The total biomass development was well calibrated indicating a good coverage of the physiological characteristics of the sorghum varieties.

Generally, model evaluation with the calibrated cultivar-specific parameters provide good agreement between simulated and observed values for crop phenology within the limits of experimental error. The results show RMSE values of ≤ 3 days for number of days to 50% flowering and ≤ 4 days for a number of days to physiological maturity (Table 4). However, days to physiological maturity was simulated with higher accuracy than days to 50% flowering for both cultivars possibly reflecting the additive effects of errors simulating the intermediate flowering and grain fill stages. For grain yield and total biomass, the model performance was excellent for improved Deko (medium maturing cultivar), represented by very low absolute RMSE values and $RMSE_n$ (%). The RMSE values of 11.1 and 13.9% of the observed mean was estimated for total biomass and grain yield, respectively. The model performance for predicting biomass and grain yield of ICSV-40 (early maturing cultivar) was overall good, indicated by the fairly low accuracy with RMSE values of 20.3 and 23.7%. The accurate prediction of grain yield and total biomass of both varieties under optimum condition at different planting dates with low RMSE values implies that the model could be used to reduce production either at high N or low N input levels, this was agreed with the opinion of Liu et al. (2011) and Adnan et al. (2017).

Grain yield, total biomass and water use efficiency under different N-applications

Long term simulation (>30-year period) across the three sites by APSIM model for grain yield and total biomass were quite satisfactorily under different N-fertilizer rates from 0 to 100 kg ha^{-1} with the different plant available water capacity (PAWC; Table 5 and Figure 3). The results indicate that APSIM model is able to capture the yield response to N-fertilizer applications. Though, there was little response displayed by seasonal rainfall (440–770 mm) variability on simulated yield with coefficient of variation (CV) in year for both grain yield and total biomass ranged from 5.5 to 13.2% (Table 5). Thus, sorghum cultivars response to N-application rate indicates higher yield variability simulated in Sokoto and Kano than Samaru (Figure 3). This implies that yield losses for early to medium maturing sorghum cultivars may not be associated to erratic rainfall pattern but rather lack of nitrogen in the soil because the physiological potential of the cultivars falls within received in-season rainfall. It is, however, expected that the increase temperature might have a more severe impacts on sorghum productivity as it accelerates vegetative growth and maturity processes irrespective of whether rainfall increases or decreases in the semi-arid area (Sultan et al. 2014; Sennhenn et al. 2017).

Table 5. Mean grain yield, total biomass and water use (WU) variations of sorghum cultivars simulated by APSIM under varying N-fertilizer applications in Sokoto (Sudano-Sahelian zone), Kano (Sudan savanna zone) and Samaru (Northern Guinea Savanna zone).

N-Treatment /Cultivar	Sokoto			Kano			Samaru		
	Grain yield	Total biomass	Water Use (WU)	Grain yield	Total biomass	Water use (WU)	Grain yield	Total biomass	Water Use (WU)
	kgha^{-1}		mm	kgha^{-1}		mm	kgha^{-1}		mm
ICSV-400									
0	1131	3761	315	1326	4406	278	2195	7396	320
20	1523	4859	323	1718	5628	291	2422	8206	330
40	2120	6737	343	2517	8254	324	2688	9208	343
60	2262	7221	350	2816	9308	341	2748	9543	347
80	2324	7466	353	3000	10,042	354	2758	9618	348
100	2335	7533	354	3056	10,598	363	2759	9624	348
LSD (0.05)	93	327	4.2	65	137	3.9	37	153	2.0
CV of Year (%)	10.3	11.2	9.9	7.3	7.0	9.2	5.5	6.2	8.7
Improved Deko									
0	1114	4517	331	1246	5096	302	2104	8389	346
20	1368	5497	340	1541	6234	316	2388	9428	356
40	2030	7596	361	2464	9287	353	2656	10,765	372
60	2188	8285	368	2824	10,868	378	2708	11,193	377
80	2237	8578	372	2980	11,882	395	2722	11,509	381
100	2250	8722	373	3038	12,547	407	2734	11,777	384
LSD (0.05)	115	417	5.6	61	168	5.2	41	266	3.6
CV of Year (%)	13.2	12.5	9.3	7.9	7.4	9.4	7.2	7.2	8.0
ANOVA									
N-rates (N)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
Cultivar (C)	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001	<.001
C × N	ns	ns	ns	<.001	<.001	<.001	ns	<.001	<.001

LSD (.05) - least significant difference of mean at 5% level of probability; CV: Coefficient of variation in year.

Furthermore, the analysis of variance (ANOVA) indicates that simulated grain yield and total biomass were highly significant ($p < .001$) due to N-application rates and cultivars while significant interaction of N-rate and cultivar (N × C) existed only for grain yield and total biomass in Kano and total biomass in Samaru (Table 5). In the Sudano-Sahelian zone represented by Sokoto the mean grain yield of ICSV-400 simulated across N levels ranged from 1131 kg ha^{-1} to 2335 kg ha^{-1} while those for Improved Deko ranged between 1110 and 2250 kg ha^{-1}, respectively (Table 5). Figures 3a, b show that increase N-fertilizer rates increased grain yield proportionally up to 100 kg N ha^{-1}. The yield variability (1328–2631 kg ha^{-1} for ICSV-400 and 1289–2669 kg ha^{-1} for Improved Deko) were significantly higher from 0 to 40 kg N ha^{-1} when compared to N-rate of 60 and 100 kg N ha^{-1}. The mean highest values of 2335 kgha^{-1} for ICSV-400 and 2250 kgha^{-1} for Improved Deko were simulated at 100 kg N ha^{-1}, while the least simulated yield was obtained at 0 kg N ha^{-1} treatment. As shown in Table 4, there were no significant mean yield difference between N-rates at 60 and 100 kgha^{-1} suggesting optimal mean grain yield of 2262 kg ha^{-1} for ICSV-400 and 2188 kg ha^{-1} at application rates of 60 kg N ha^{-1}. The increase in N-fertilizer rate increased simulated grain yield by 26–52% for ICSV-400 and 19–50% for Improved Deko compared to zero fertilizer treatment. Similar to grain yield, total biomass increased with increase in N-fertilizer rates, the mean simulated ranged from 3760 to 7535 kgha^{-1} for ICSV-400 while values for improved Deko ranged from 4520 to 8722 kgha^{-1}. The result further shows that N-fertilizer increased total biomass by 43% for ICSV-400 and 40% for Improved Deko compared to no fertilizer treatment.

In the Sudan savanna zone represented by Kano, the mean simulated grain yield ranged from 1326 kg ha^{-1} to 3056 kg ha^{-1} while those for Improved Deko ranged from 1246 to 3038 kg ha^{-1}, respectively (Table 4). The probability of exceedance indicates (Figures 3c, d) higher yield variability among N-treatment from 0 to 60 kg N ha^{-1} when compared with simulated yield between 80 and 100 kg N ha^{-1} suggesting optimal mean grain yield of 3000 kg ha^{-1} for ICSV-400 and

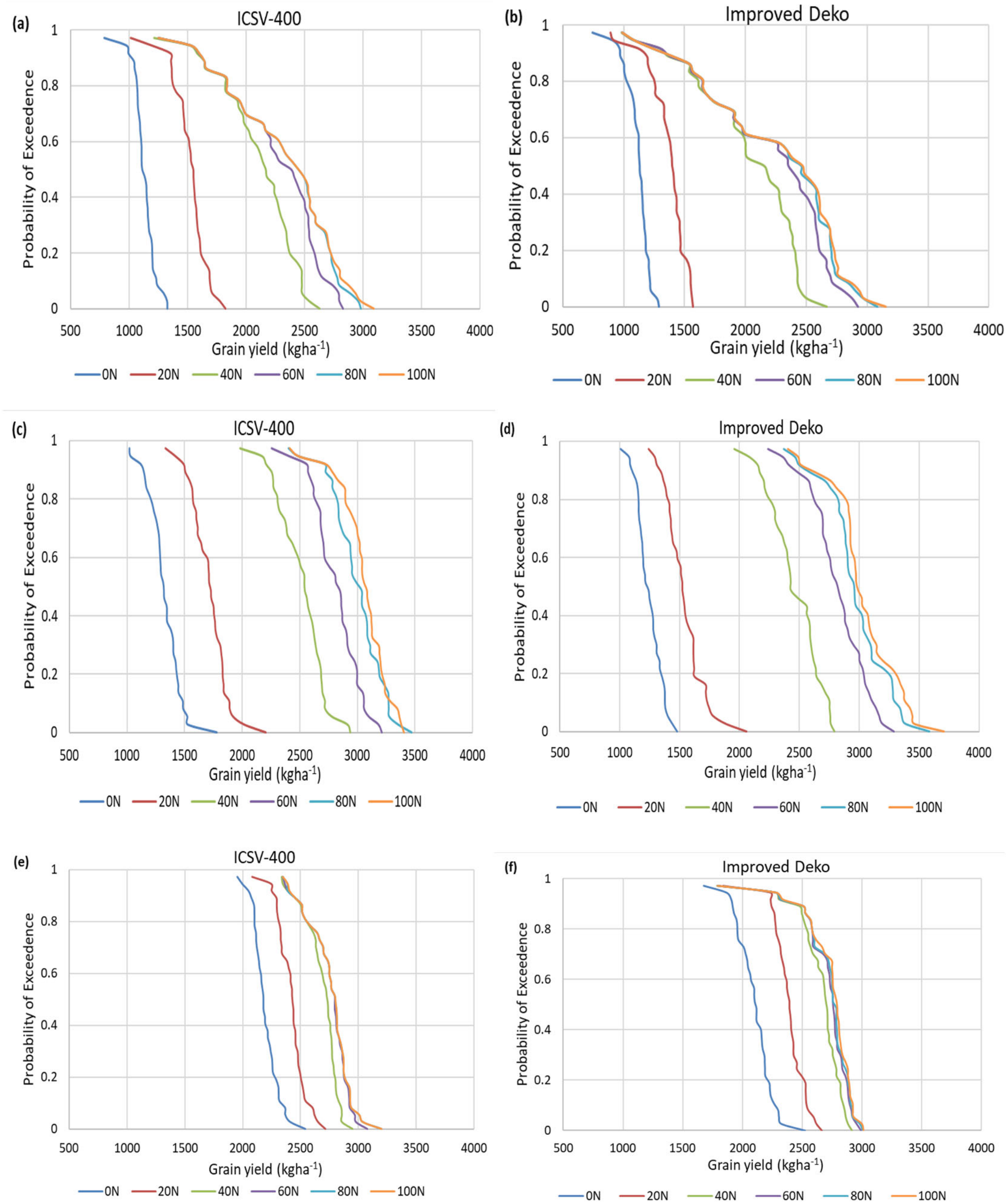

Figure 3. Probability of exceedance for simulated grain yield of ICSV-400 and Improved Deko in Sokoto (a & b), Kano (c & d) and Samaru (e & f) representing three agroecological zones indicating different soil plant available water capacity (PAWC) based on long-term current climatic condition.

2980 kg ha^{-1} at application rates of 80 kg N ha^{-1}. Application of N-fertilizer increased simulated grain yield by 23–57% for ICSV-400 and 19–59% for Improved Deko compared to zero fertilizer treatment. Total biomass increased with increased fertilizer rates from 0 to 100 kg N ha^{-1}(Table 4), the mean simulated yield ranged from 4406 to 10,598 kgha^{-1} for ICSV-400 while improved Deko ranged from 5096 to 12,547 kg ha^{-1}. The results further indicated that N-fertilizer increased simulated total biomass by 47% for both cultivars compared to zero fertilizer treatment.

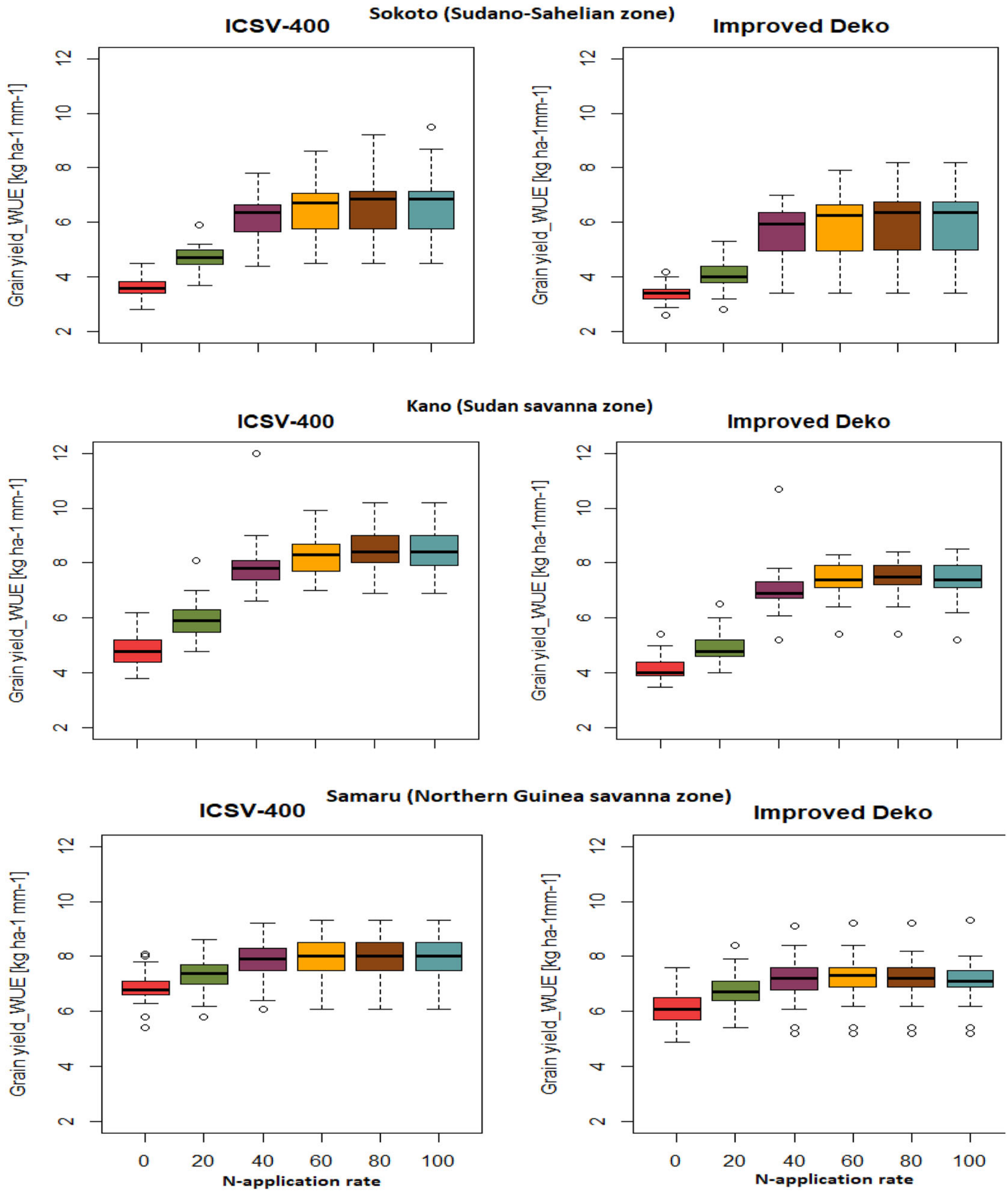

Figure 4. Boxplots of simulated grain yield water use efficiency (GY_WUE) for ICSV-400 and Improved Deko at different agroecological zone under different soil plant available water capacity (PAWC) based on long-term simulation (1981–2017).

In Northern Guinea savanna zone represented by Samaru site, the probability of exceedance indicates (Figures 3e, f) low yield variability among N-treatment, but significant yield variations existed from 0 to 40 kg N ha^{-1} while simulated yield between 60 and 100 kg N ha^{-1} remain more or less constant. However, considering the magnitude of mean grain yield (~60 kg) difference between 40 and 60 kg N ha^{-1}, it shows increase N-rate beyond 40 kgha^{-1} will not lead to a significant increase in yield suggesting optimal grain yield at 40 kg N ha^{-1}. The mean simulated grain yield ranged from 2195 kg ha^{-1} to 2759 kg ha^{-1} while those for Improved Deko ranged between 2104 and 2734 kg ha^{-1}, respectively (Table 5). The increase N-fertilizer rate increased simulated grain yield by 8–20% for ICSV-400 and 12–23% for Improved Deko compared to zero fertilizer treatment. Also, the mean simulated total biomass ranged from 7396 to 9624 kgha^{-1} for ICSV-400 while improved Deko ranged from 8389 to 11,777 kgha^{-1} which indicates N-fertilizer increased total biomass by 20% for ICSV-400 and 23% for Improved Deko.

The simulations displayed that the combined soil evaporation and crop transpiration (i.e., evapotranspiration) for different soils and sites across N-treatment was not consistent. Mean simulated WU was significantly different among N- fertilizer rate from 0 to 100 kg ha^{-1} in Kano and Samaru while no significant difference was observed in Sokoto. In Sokoto, the Simulated WU ranged from 315 to 354 mm for ICSV-400 and 331 to 373 mm for Improved Deko. The results also showed that simulated WU for Kano ranged from 278 to 363 mm for ICSV-400 and 302 to 407 mm for Improved Deko while values for Samaru ranged from 320 to 348 mm for ICSV-400 and 346 to 384 mm for Improved Deko, respectively. Subsequently, the grain water use efficiency (WUE_{grain}) was statistically different for ICSV-400 and Improved Deko across N-fertilizer rates and different sites (Figure 4). Mean WUE_{grain} was always higher for ICSV-400 than Improved Deko across N-application rates, which was statistically significantly higher in Samaru and Kano than Sokoto. Similarly, high WUE_{grain} variability was simulated among N-application rate in Sokoto and Kano while low WUE_{grain} variability was simulated in Samaru. The variability across the sites may be due to in-crop seasonal rainfall distribution. In Sokoto, the average WUE_{grain} ranged from 3.6 to 6.6 kg ha^{-1}mm^{-1} for ICSV-400 and 3.4 to 6.0 kg ha^{-1}mm^{-1} WU for Improved Deko. Mean WUE_{grain} for Kano was slightly higher than Samaru which ranged from 4.8 to 8.6 kg ha^{-1}mm^{-1} E_t for ICSV-400 and 4.1 to 7.6 kg ha^{-1}mm^{-1} for Improved Deko. Meanwhile, simulated mean WUE_{grain} for Samaru ranged from 6.9 to 8.0 kg ha^{-1}mm^{-1} for ICSV-400 and 6.1 to 7.2 kg ha^{-1}mm^{-1} for Improved Deko. Also, there were significant differences for simulated WUE_{grain} at N-application rates from 0 to 40 kg ha^{-1} while no significant difference observed for simulated WUE_{grain} between 60 and 100 kg N ha^{-1}. The results indicate that N-application rate beyond 40 kgha^{-1} has no extra demand for water utilization across the three agroecological zones. Also, mean simulated WUE_{grain} was in general lower at drier areas (Sokoto and Kano) than that of the wetter area (Samaru) for both sorghum cultivars, presumably because a greater proportion of crop water use was lost by soil evaporation (Bell et al. 2012).

Conclusion

Our study focused on response of N-fertilizer applications on sorghum yield and water productivity using APSIM. The APSIM model was well calibrated and evaluated for phenological traits (flowering and maturity) with high accuracy while grain yield and total biomass of both sorghum cultivars were evaluated with fairly low accuracy. Thus, APSIM model captured best for medium-maturing cultivars compared to early-maturing cultivar. The study also found APSIM model as a useful tool that can helps optimizing N-fertilizer application strategies to obtain the maximum economic productivity and environmental adapted efficiency for sorghum in the study areas. The comprehensive analysis of the long-term weather records, identified the impacts of inter-annual variability and associated risks on the both early and medium sorghum varieties in the three agroecological zones. The simulation confirmed that the two sorghum cultivars followed the physiological strategy of drought escape (early cessation of rainy season) as both flowering and physiological maturity coincided within the length of growing season (LGS) across the zones. The low variability of simulated grain yield to increase N levels at Samaru suggests sorghum requires less N in this zone probably due to high organic carbon and residual N in this wet zone. Since organic carbon is higher in Samaru and clay and silt content are also higher than in the drier locations, nitrogen released from the organic matter and the high nutrient retention make a lot of N available to the sorghum plant which reduces the need for more N to be applied beyond 40

$kgha^{-1}$ compared to other two locations (Kano and Sokoto). Therefore, the optimal N-rates for the simulated yield in the three selected sites suggest current review of the recommended N- fertilizer rates for sorghum because they do not take into account the inherent soil fertility differences and rainfall distribution in all the locations within semi-arid agroecological zones.

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