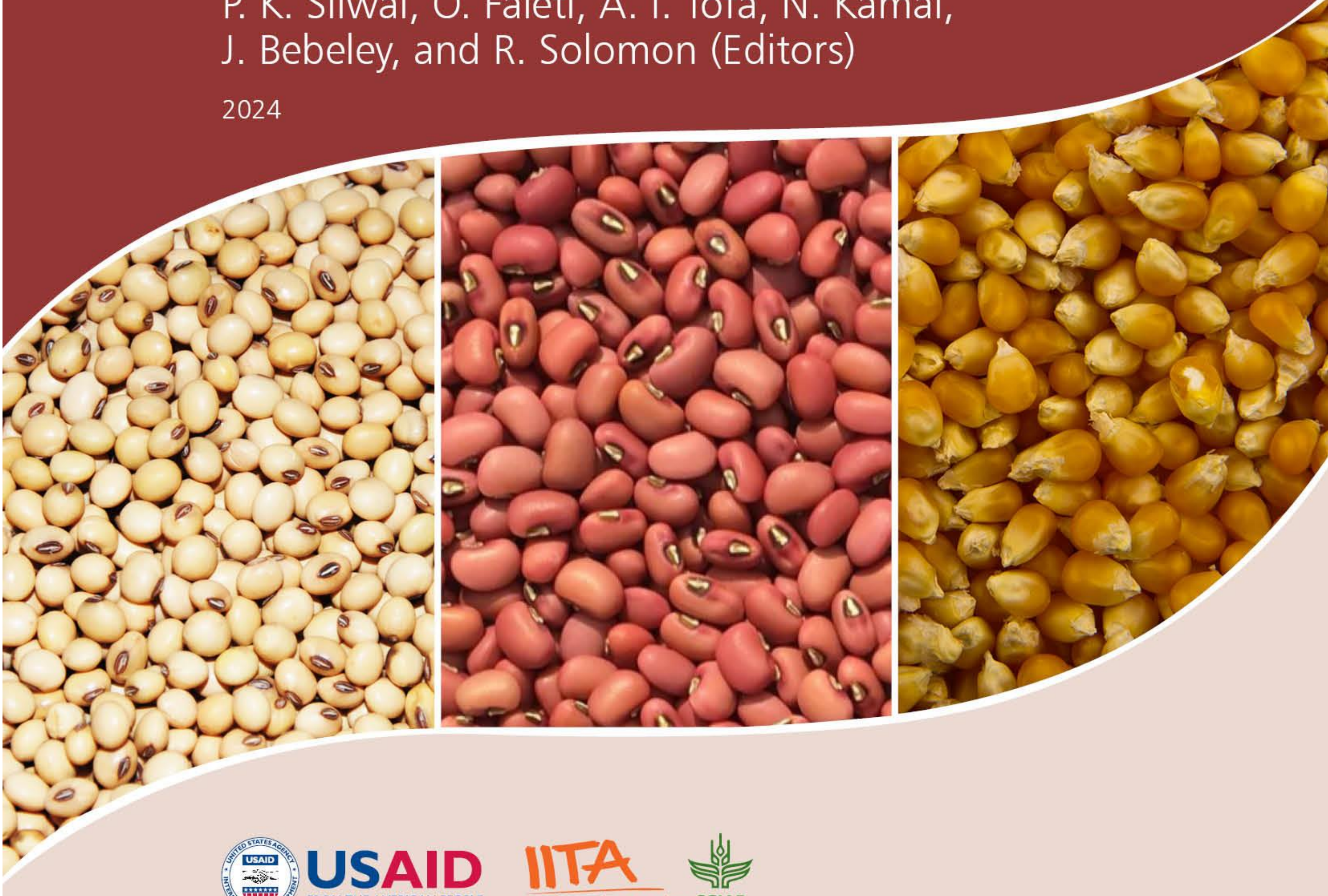
FEED THE FUTURE
The U.S. Government's Global Hunger & Food Security Initiative

Matching cereal and legume crop varieties to production environments in Northeast Nigeria using Decision Support Tools (DST)

H. A. Ajeigbe, A. Y. Kamara, F. M. Akinseye, P. K. Silwal, O. Faleti, A. I. Tofa, N. Kamai, J. Bebeley, and R. Solomon (Editors)

2024



USAID FROM THE AMERICAN PEOPLE
IITA Transforming African Agriculture
CGIAR

www.iita.org

Matching cereal and legume crop varieties to production environments in Northeast Nigeria using Decision Support Tools (DST)

H.A. Ajeigbe, A.Y. Kamara, F.M. Akinseye,
P.K. Silwal, O. Faleti, A.I. Tofa, N. Kamai,
J. Bebeley, and R. Solomon (Editors)

2024

Published by the International Institute of Tropical Agriculture (IITA), 2024

International address:
IITA, Grosvenor House,
125 High Street
Croydon CR0 9XP, UK

Headquarters:
PMB 5320, Oyo Road
Ibadan, Oyo State

ISBN 978-978-131-425-4

Printed in Nigeria by IITA

Citation: H.A. Ajeigbe, A.Y. Kamara, F.M. Akinseye, P.K. Silwal, O. Faleti, A.I. Tofa, N. Kamai, J. Bebeley, and R. Solomon (Editors). 2024. Matching cereal and legume crop varieties to production environments in Northeast Nigeria using Decision Support Tools (DST). International Institute of Tropical Agriculture (IITA). 92 pp.

Contents

Foreword

The violence perpetrated by religious extremist and later by bandits and kidnappers have devastated much of North-East Nigeria during the past 12 years. These terrorist threats are impeding civil progress, restricting agricultural activities and resulting in a major displacement of local populations. At the same time, agriculture is facing several constraints including climate change, drought, poor soils, pest and diseases, weak economic infrastructure and markets, and paucity of progressive policies that support agricultural development. The resultant low agricultural productivity has led to alarming rates of food and nutritional insecurity, too limited livelihood opportunities, chronic underemployment, and severe malnutrition. However, improved technologies, practices and innovations are available to address these agricultural constraints.

The Feed the Future Nigeria Integrated Agriculture Activity (IAA) issued under the US Government's Global Food Security Act was awarded by USAID Nigeria to IITA and its partners on 19th July 2019 as part of USAID's contributions to the economic recovery in the North-East, in the aftermath of the on-going insurgency in the region. IAA supports vulnerable populations to engage in basic farming activities that will improve food security, increase agricultural incomes, and improve resilience among smallholder farmers and their families in Adamawa and Borno states. IAA works with a coalition of public and private sector partners to facilitate improved agro-inputs and extension advisory services to serve vulnerable populations, strengthen the institutions that form the market system and the networks that serve smallholder farmers who have been disenfranchised by conflict, and facilitate the engagement of youth and women in commercial agribusiness activities.

IITA being a science-based organisation uses science based and proven market-oriented tools starting from identification of climate resilient and market-oriented varieties of component crops. The book "Matching cereal and legume crop varieties to production environments in northeast Nigeria using decision support tools (DST)" reports on the simulation of the performance of the widely grown improved varieties of cereals and legumes using two sets of decision support tools; Decision Support Tools for Agricultural Technology Transfer (DSSAT) model and the Agricultural Production simulation model (APSIM) to recommend those that are most suitable to the agroecology in which the project works (Adamawa and Borno States). These are then deployed with improved agronomic practices and new technologies by the Activity to achieve great results.

This book is intended to guide farmers, extension personnel, students of agriculture in higher institutions, researchers, and other development projects on the improved varieties of legumes and cereals to use or promote in Northeast Nigeria especially in Adamawa and Borno States to increase productivity.

Kenton Dashiell
Deputy Director General, Partnerships for Delivery/General Directorate
International Institute of Tropical Agriculture (iita.org)

Acknowledgment

We acknowledge the many people who have contributed to the development of this book other than the listed authors, especially the Feed the Future (FtF) Nigeria Integrated Agriculture Activity team for their tireless efforts and immense contribution towards the achievement of the Activity's objectives. The Officials of the Adamawa and Borno States ADPs as well as the field and Extension Agents, were very helpful during the fieldwork that involved digging in several sites and farms. Most importantly we are grateful to the nice and hardworking farmers of these states for not only cooperating with us to dig profile pits in their farms but on most occasions also assisting us in the work as well as providing valuable information about the land use history.

We thank the Management of IITA led by the Director General, Dr. Simeon Ehui, Dr. Kenton Dashiell, Dr. Alfred Dickson, Dr. Robert Asiedu, Dr. Gbassey Tarawali, and others who provided valuable advice and contributions to the project development and implementation. We also appreciate colleagues of IITA and ICRISAT at Kano Station for their assistance.

Finally, we thank Dr. Ayoade Adetoye, the Activity's AOR and his other colleagues at USAID (past and present) who have provided their active support in terms of providing technical guidance in making sure that we follow USAID rules and regulations, and the documents are of quality.

This publication is a production of the Feed the Future Nigeria Integrated Agriculture Activity implemented in targeted locations of Adamawa, Borno, Gombe and Yobe states, Nigeria between 2019 and 2024, and was made possible through financial support from the United States Agency for International Development (USAID).

Abbreviations and Acronyms

ABU	Ahmadu Bello University
ABCOA	Audu Bako College of Agriculture
ADP	Agricultural Development Project
APSIM	Agricultural Production simulation model
DSSAT	Decision Support Tools for Agricultural Technology Transfer
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization and Statistical Database
FMARD	Federal Ministry of Agriculture and Rural Development
IAA	Integrated Agriculture Activity
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
NAERLS	National Agricultural Extension Research and Liaison Services
USAID	United States Agency for International Development

Chapter 1

Introduction

Maize, millet, and sorghum are the most important cereal crops in northern Nigeria (Ajeigbe et al., 2018, Kamara al., 2020). These cereal crops provide the calorie needed for the households in this region. In addition to the cereals, legume crops such as cowpea, groundnut and soybean are important components of the farming systems. They are cheap sources of food and feed because of their high protein content.

Groundnut and soybean are also important cash crops because of their use in the processing industry for oil and animal feeds. Nigeria is the largest producer of millet, sorghum, and cowpea and second largest producer of maize, groundnut in Africa (FAOSTAT, 2020). Nigeria produces 2.61 million tons of cowpea, 2.89 million tons of groundnut, 10.15 million tons of maize, 2.24 million ton of millet, 6.86 million tons of sorghum, and 0.76 million tons of soybean in 2018.

All the cereal and legume crops produced in northern Nigeria are also produced in northeast Nigeria because of the availability of diverse growing environments covering the Guinea, Sudan and the Sahel savannas. Despite the importance of these crops in Nigeria, yields are low compared to other countries. According to FAO, yields obtained on farmers' fields are 913, 991, 2092, 801, 1120, and 971 kg/ha for cowpea, groundnut, maize, millet, sorghum and soybean, respectively (FAOSTAT, 2018, 2020).

The yields of cereals and legumes are limited by several constraints in the Nigeria savannas. In the northeast Nigeria, poor soil fertility, intermittent drought, infestation of crop lands by parasitic weeds, and pest and diseases significantly reduce crop yields. For example, yield loss of up to 60-80% are reported due to low plant nutrients and drought (Kamara et al., 2013). If these stresses occur together with pest and disease attacks, total yield loss of the crops will occur. Several agronomic technologies have been developed to address the effects of these biotic and abiotic constraints. For example, several Striga-resistant and drought-tolerant cowpea and maize varieties (Kamara et al, 2013; Menkir et al., 2016; Omoigui et al., 2017).

Striga and drought-tolerant varieties of millet (Ajeigbe et al., 2019) and sorghum varieties (Ajeigbe et al., 2018) have been developed. Moreover, soil and crop management practices have been developed for rapid dissemination in the Nigeria savannas along with the improved crop varieties (Adnan et al., 2017, Ajeigbe et al., 2019, Kamara et al.,2016, 2009, Akinseye et al., 2020, Tofa et al., 2020). Several field trials have been carried out in the Nigerian savanna over the past 20 years to evaluate the performance of the various crop production technologies to improve the productivity of cereal and legume crops.

To be able to adequately assess the performance of these technologies across the Nigeria savannas would require the establishment of several field experiments under the different environmental conditions. Moreover, there is a need to widely disseminate the crop varieties and the management technologies in northeast Nigeria where the Feed-Future project Integrated Agriculture Activity is being implemented. To be able to this, will require widespread testing across the region to identify the most suitable technologies. However, there are inherent factors limiting the quantity of field experiments that can be conducted under different soil types and climate conditions in this region, including economic and time constraints. The soils in the region are heterogenous and the weather is very variable which makes it impossible to extrapolate results from one location to another. Thus, crop simulation models represent a complementary approach to further investigate the potential impacts of crop varieties and management practices on grain yields of cereals and legumes across a range of environments.

Crop models are increasingly used as a tool to explore the spatio-temporal impacts of different management scenarios following calibrations at field experiments, particularly for upscaling the impacts of crop varieties and management practices from field to watershed and regional scales (Keating *et al.,* 2003). At a larger scale, prediction models may help farmers understand how to implement the most efficient management practices for a certain genotype in a certain environment.

In this booklet, we report on the simulation of the performance of the widely grown cereals and legumes in the project areas in Adamawa and Borno States using two sets of decision support tools: Decision Support Tools for Agricultural Technology Transfer (DSSAT) model and the Agricultural Production simulation model (APSIM). The booklet is divided into four sections. Section 1 provides general introduction into the problems of crop production in northern Nigeria, progress in developing technological solutions to address these constraints, and the need to use Decision Support Tools to evaluate and target the technologies to specific domains in the project areas. Section 2 describes the project sites, soils and climatic conditions. Section 3 addresses the simulation of the performance of maize, cowpea, and soybean in the selected communities in targeted Local Governments in Adamawa and Borno States using the DSSAT model. Section 4 reports on the results of the simulation of the performance of groundnut, millet, and sorghum using the APSIM model.

References

Adnan, A.A., Jibrin M.J., Kamara, A.Y., Abdulrahman, B.L., Shuaibu A.S., and Garba, I.I. (2017). CERES-Maize Model for Determining the Optimum Planting Dates of Early Maturing Maize Varieties in Northern Nigeria. *Frontiers in Plant Science,* 8: 1118.

Ajeigbe H.A., Akinseye, F.M., Ayuba, K., and Jonah, J. (2018). Productivity and Water Use Efficiency of Sorghum [*Sorghum bicolor* (L.) Moench] Grown under Different Nitrogen Applications in Sudan Savanna Zone, Nigeria. *International Journal of Agronomy*, vol 2018, Article ID 7676058, 11pp. https://doi.org/10.1155/2018/7676058

Ajeigbe, H.A., Akinseye, F.M., Kunihya, A., Abdullahi, A.I., Kamara A.Y. (2019). Response of pearl millet (*Pennisetum glaucum,* L.) to plant population in the semi-arid environments of Nigeria. *Net J Agric Sci*, 7(1): 13-22.

FAOSTAT (2018). Food and Agricultural Organization of the United Nations (FAO), FAO Statistical Database, from http://faostat.fao.org.

FAOSTAT (2020). Food and Agricultural Organization of the United Nations (FAO), FAO Statistical Database, from http://faostat.fao.org.

Akinseye, F.M., Ajeigbe, H.A., Kamara A.Y., Adefisan, E.A., and Whitbread, A.M. (2020): Understanding the response of sorghum cultivars to nitrogen applications in the semi-arid Nigeria using the agricultural production systems simulator. *Journal of Plant Nutrition*, article: https://doi.org/10.1080/01904167.2020.1711943

Kamara A.Y., Ekeleme F., Menkir A., Chikoye D., and Omoigui L.O. (2009). Influence of nitrogen fertilization on the performance of early and late maturing maize cultivars under natural infestation with *Striga hermonthica*. *Archives of Agronomy and Soil Science*, 55(2): 125-145.

Kamara, A.Y., Tofa, A.I., Boahen, S.K., Solomon, R., Ajeigbe, H.A., and Kamai, N. (2016). Effects of plant density on the performance of cowpea in Nigerian savannas. *Experimental Agriculture* p. 1 of 13 Cambridge University Press *2016* doi:10.1017/S0014479716000715.

Kamara, A.Y., Ewansiha, S.U., and Menkir, A. (2013). Assessment of nitrogen uptake and utilization in drought tolerant and Striga resistant tropical maize varieties. *Archives of Agronomy and Soil Science,* 60(2): 195-206.

Keating, B.A., Carberry P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., and Hochman, Z. (2003). An overview of APSIM, a model designed for farming systems simulation. *European Journal of Agronomy*, 18, 267-288.

Menkir, A., Crossa, J., Meseka, S., Bossey, B., Ado, S.G., Obengantiwi, K., Yallou, C.G., Coulibaly, N., Olaoye, G., and Alidu, H. (2016). Comparative performance of top-cross maize hybrids under managed drought stress and variable rainfed environments. *Euphytica*, 212: 455–472.

Omoigui. L.O., Kamara, A.Y., Alunyo, G.I., Bello, L.L., Oluoch, M., Timko, M.P. and Boukar, O. (2017). Identification of new sources of resistance to Striga gesnerioides in cowpea Vigna unguiculate accessions. *Genetic Resources and Crop Evolution* 64(5): 901-911.

Tofa, A.I., Chiezey, U.F., Babaji, B.A., Kamara, A.Y., Adnan, A.A., Beah, A., Adam, A.M. (2020). Modeling Planting-Date Effects on Intermediate-Maturing Maize in Contrasting Environments in the Nigerian Savanna: An Application of DSSAT Model. *Agronomy, 10*, 871.

Chapter 2

Project sites, soils, and weather

Abstract

The performances of the cereal (maize, sorghum, millet and rice) and legume (cowpea, soybean and groundnut) varieties were simulated in 19 communities across 10 Local Government Areas (LGAs) in Adamawa State and in 15 communities across 5 LGAs in Borno State. These covered the northern Guinea savanna (NGS) zone, southern Guinea savanna (SGS) and Sudan Savanna (SS) zones in the two states. For soil characterization and soil sampling, profile pits were dug in the selected sites in both States (Adamawa and Borno). The profiles and soil types were classified using the FAO guidelines. Soil samples collected were shipped to IITA, Ibadan, Nigeria for analysis. All laboratory analyses were carried out at the Analytical Services Laboratory of IITA. Long-term weather data was sourced from gridded downscaled Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for daily rainfall (Funk et al., 2015) and National Aeronautics and Space Administration (NASA) database for Climatology Resource for Agroclimatology http://power.larc.nasa.gov/that include minimum and maximum air temperature and solar radiation. Thereafter, the two datasets were merged using R scripts were developed to append CHIRPS and NASA power data together and convert each location into a format readily ingestible by the APSIM model for the 33 selected sites. For the long-term simulation, the soil parameters used for both models (DISSAT and APSIM) were obtained from on-site soil characterization using geospatially buffering points in at least 20 km radius using ArcGIS map of the reference indicating the sites/LGAs. The results of the weather data and soil analysis are given below. Thess were used to for the simulation exercise.

2.1. Project Sites

The performance of the cereal and legume varieties was simulated in 19 communities across 10 Local Government Areas (LGAs) in Adamawa State and in 15 communities across 5 LGAs in Borno State (Table 1 and Fig. 1).

In Adamawa most of the LGAs are in the northern Guinea savanna (NGS) zone except Fufore in Yola south, Yalwa Dembore in Yola north and Nassarawo-Demsa in Demsa LGA, which lie in the southern Guinea savanna (SGS) and Dulmava in Hong and Guyaku in Gombi LGA which lie in the Sudan Savanna (SS) zones.

In Borno States, most of the targeted LGAs are in Sudan savanna except Gwaskara, Kubo and Lakundum in Shani LGA which are in the northern Guinea savanna zone. In the SGS, temperature varies annually and seasonally over the zone with average maximum temperature in the growing season within the range of 26-28^{o}C whereas minimum temperature ranges between 18-22 ^{o}C (Omotosho et al. 2013; Ayanlade, 2016).

Rainfall distribution in the zone is unimodal. Average annual rainfall range between 1000 mm to 1524 mm and spread over 181-210 days which defines the growing season (Jagtap, 1995; Ayanlade, 2016). The soils in this zone have been identified mainly as Lithosols, Ferralic combisols, Feric acrisols, Oxic haplustalfs and Luvisols (FAO/UNESCO, 1974).

In the NGS, the length of growing period is between 151-180 days (Jagtap, 1995). It has a unimodal rainfall distribution averaging between from 900 to 1000 mm annually, and maximum temperatures varied from 28 to 40°C (Atehnkeng *et al.,* 2008). According to world reference base FAO classification, the dominant soil in the NGS are Luvisols (FAO, 2006). The Sudan savanna is characterized by high annual temperature (28-32 °C), short growing season around 90 days and low rainfall ranging from 600 to 800 mm (Adnan et al., 2017). The soil of the Sudan savanna is sandy and porous, with rapid drainage of water. The dominant soil types mainly found in the zone are Alfisols, and Entisols according to world reference base FAO classification.

Table 2.1 Summary of the project sites that were used for simulation of crop performance.

S/No	State	_LGA	_Location	AEZ	Code	Longit.	Lat.
1	Adamawa	Demsa	Mbula Kuli	NGS	DMK	12.301568	9.457453
2		Demsa	Nassarawo Demsa	SGS	DNS	12.150069	9.296248
3		Girei	Wuroshi	NGS	GJB	12.616352	9.468659
4		Girei	Daneyel	NGS	GIT	12.513956	9.547608
5		Gombi	Tawa	NGS	GOT	12.685600	10.169090
6		Gombi	Guyaku	SS	GOG	12.663390	10.345880
7		Guyuk	Chikila	NGS	GUC	11.971910	9.772365
8		Guyuk	Lakumna	NGS	GUG	11.989722	9.920833
9		Hong	Dulmava	SS	HOB	12.982394	10.301400
10		Hong	Hushere Zum	NGS	HOH	13.080656	10.103753
11		Numan	Bare	NGS	NB	12.110769	9.584298
12		Numan	Kikan_Kodomti	NGS	NK	11.987783	9.460814
13		Shellenge	Jonkolo - Lama	NGS	SHEG	12.177973	9.899652
14		Sheleng	Lakati_Libbo/	NGS	SHEWY	12.250196	9.695414
15		Song	Sabon Gari	NGS	SOSG	12.593541	9.840488
16		Song	Suktu	NGS	SOS	12.424821	9.637458
17		Yola North	Yelwa -Jambore	SGS	YNY	12.504630	9.261650
18		Yola South	Fufure	SGS	YSNG	12.650420	9.173600
1	Borno	Bayo	Balbaya	SS	BABL	11.764809	10.584837
2		Bayo	Briyel	SS	BABR	11.649672	10.371014
3		Bayo	Jara-Dali	SS	BAJD	11.731594	10.275863
4		Biu	Buratai	SS	BIB	12.415800	10.767500
5		Biu	Kabura	SS	BIK	12.265300	10.739200
6		Biu	Mathau	SS	BIM	12.109700	10.721400
7		Biu	Tum	SS	BIT	12.488100	10.822800
8		Hawul	Kwajaffa	SS	HAK	12.483106	10.516721
9		Hawul	Puba Vidau	SS	HAPV	12.187900	10.522375
10		Hawul	Sakwa Hema	SS	HASH	12.389373	10.386722
11		Kwayakusar	Bila Gusi	NGS	KKBG	12.047606	10.519175
12		Kwayakusar	Kurbo Gayi	SS	KKKG	11.957516	10.384040
13		Shani	Gwaskara	NGS	SHAG	12.158012	10.227146
14		Shani	Kubo	NGS	SHAK	12.085300	10.140000
15		Shani	Lakundum	SS	SHAL	12.050556	10.055556

***LGA** = Local Government Area, **AEZ**=Agro-ecological zone*

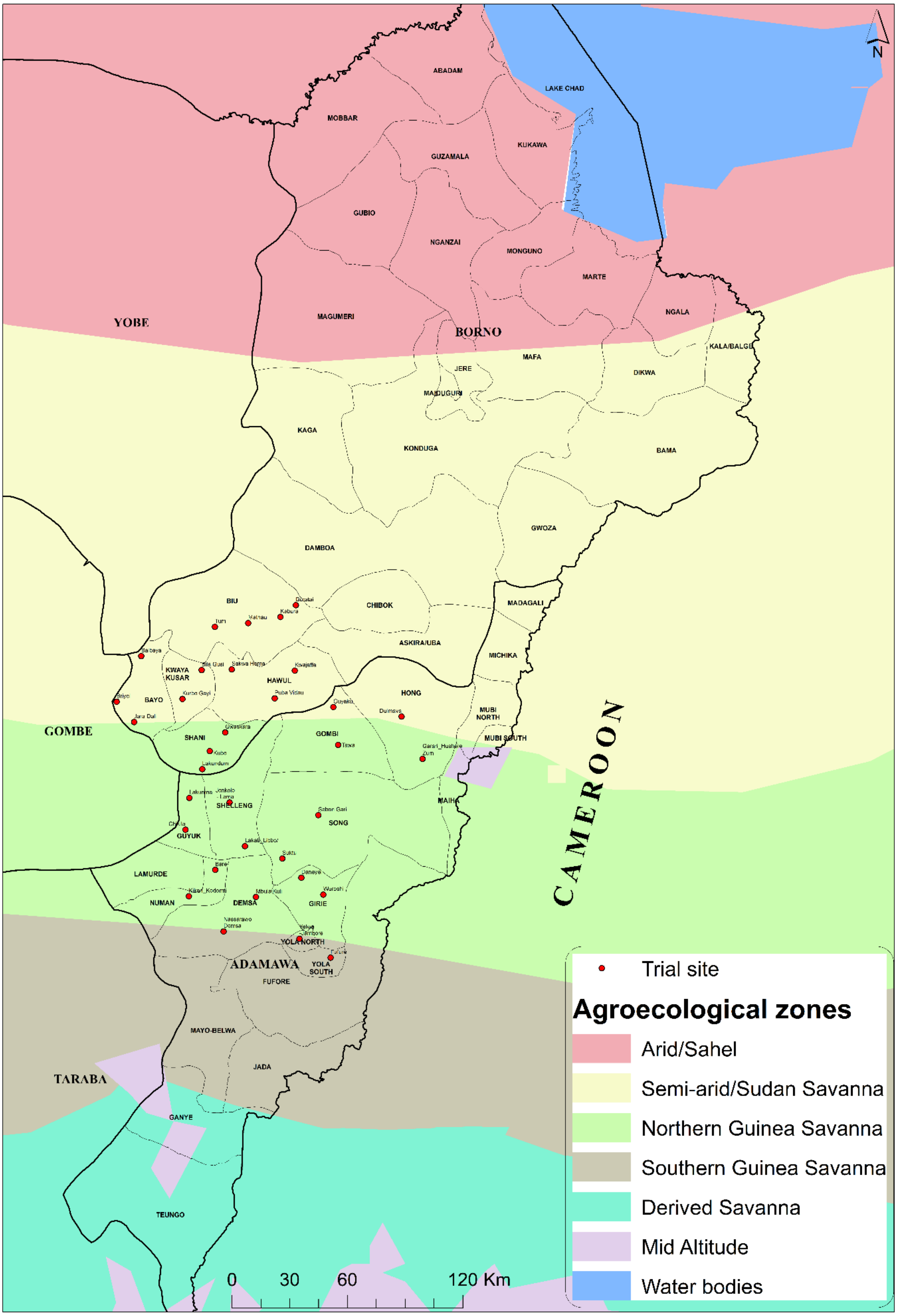


Fig. 2.1. Map showing Study areas in Adamawa and borno states

2.2. Soil Fertility Assessment

2.2.1 Methodology

For the long-term simulation, the soil parameters used for the both models were obtained from on-site soil characterization using geospatially-buffering points in at least 20 km radius using ArcGIS map of the reference indicating the sites/LGAs. For soil characterization and soil sampling, profile pits were dug in the selected sites in both States (Adamawa and Borno). The profiles and soil types were classified using the FAO guidelines (FAO, 2006). Soil samples collected were shipped to IITA, Ibadan, Nigeria for analysis. All laboratory analyses were carried out at the Analytical Services Laboratory of IITA. Total soil organic carbon (total C) was measured using a modified Walkley and Black chromic acid wet chemical oxidation and spectrophotometric method (Heanes, 1984). Total nitrogen (total N) was determined using a micro-Kjeldahl digestion method (Bremner, 1996). Soil pH in water (S/W ratio of 1:2.5) was measured using a glass electrode pH meter and the particle size distribution following the hydrometer method (Gee and Or, 2002). Available phosphorus was extracted using the Bray 1 method (Bray and Kurtz, 1945). Phosphorus in the extract was determined colorimetrically by the molydo-phosphoric blue method using ascorbic acid as a reducing agent. K was analyzed based on Mehlich 3 extraction procedure (Mehlich, 1984).

2.2.2 Results

According to the soil analysis, most of the topsoils in Adamawa State were coarse textured with higher sand contents. Out of the 18 study sites, 72% had sandy loam, 17% clay, and 11% sandy clay loam texture (Table 2). The soil pH for the communities in Adamawa State ranged from 5.9 (Jonkolo-Lama in Shelleng) to 9.0 (Fufore in Yola South). More than 55% of the soils had slightly acidic (6.1–6.5) to neutral (7.3–7.8) soil reactions. The soil organic carbon (OC) contents in the State ranged from 0.22% in Daneyel in Girei LGA and Suktu in Song LGA to 0.90% in Guyuk area. The distribution of soil in the study areas showed that most of the soils (67%) in the State had low (0.4 – 1.0%) OC levels. The total soil N contents in the soils ranged from very low (< 0.05%) to low (0.06-0.1%) and 67% of the study locations in State fell within the very low N fertility class. The soil available P varied among the locations with very low (< 3.0 mg kg^{-1}) at Woroshi in Girei, Tawa in Gombi, Chikila in Guyuk, Lakumna in Guyuk, Dulmava in Hong, Hushere-Zum in Hong, Jonkolo-Lama in Shelleng, Sabon-Gari in Song and Yelwa-Jambore in Yola North LGA; low available P (3 - 7 mg kg^{-1}) was found in Demsa-Nassarawa in Demsa LGA, Bare in Numan, Lakati-Libbo in Shelleng and Suktu in Song LGA, while high P (> 20 mg kg^{-1}) contents were found in Mbula kuli in Demsa LGA, Kikan_Kodomti in Numan and Fufore in Yola South LGA. This indicated that, 50% of the study locations in State fell within the very low P fertility class. Exchangeable K levels were moderate (0.3 $cmol^{+}$ kg^{-1}) to high (> 0.3 $cmol^{+}$ kg^{-1}) in 78% of the locations.

Table 3 shows the summary of topsoil properties of pedons used for model applications in Borno State. Majority of the subsurface soils were also coarse textured with higher sand contents, out of the 15 study sites 47% had sandy loam, 27% clay, and 26% s loamy sand texture. The soil pH for the communities in Borno State ranged from 6.1 (Balbaya) to 8.4 (Briyel) in Bayo LGA. More than 70% of the soils had slightly acidic (6.6 – 7.2) to slightly alkaline (7.3 – 7.8) soil reactions. The soil OC contents in the State ranged from 0.12% at Mathau to 0.78% at Kabura in Biu area. Eight (8) communities equivalent to 53% of the study area had very low OC (< 0.4%) level. The total soil N contents in the soils ranged from very low to low fertility status with very low (< 0.05%) status found in Balbaya, Bila Gusi, Briyel, Buratai, Gwaskara, Jara-Dali, Kubo, Kurba, Mathau, Puba Vidau, Sakwa-shema and Tum communities, while Kabura, Kwajaffa and Lakundum communities fell within the low (0.06-0.1%) N fertility class. With the exception of

Gwaskara in Shani LGA the topsoil available P at all the locations in Borno State fell within very low (< 3.0 mg kg^{-1}) fertility class. This indicated that, 93% of the study locations in State fell within the very low P fertility class. Exchangeable K levels were 7% low (< 0.15 $cmol^{+}$ kg^{-1}); 33% moderate (0.16 - 0.3 $cmol^{+}$ kg^{-1}); 60% high (> 0.3 $cmol^{+}$ kg^{-1}) in the State.

Table 2.2 Subsurface physical and chemical properties used for model applications in Adamawa State.

Location LGA	Community	Profile depth (cm)	BD (g/cm^3)	OC (%)	Sand (%)	Silt (%)	Clay (%)	pH (in $H_2$0)	N (%)	Meh. P (ppm)	K cmol/kg
Demsa	Mbula-Kuli	0-20	1.76	0.84	59	23	18	7.8	0.06	32.1	0.5
Demsa	Nassarawo-Demsa	24-180	2.18	0.66	65	15	20	8.3	0.06	3.8	0.89
Girei	Daneyel	31-200	1.76	0.22	81	7	12	7.0	0.01	10.9	0.3
Girei	Woroshi	14-94	2.16	0.54	65	19	16	6.4	0.04	1.17	0.36
Gombi	Guyaku	19-120	1.7	0.35	79	9	12	6.6	0.03	2.14	0.22
Gombi	Tawa	15-127	1.79	0.62	75	13	12	6.7	0.05	3.38	0.21
Guyuk	Chikila	30-180	2.18	0.90	15	19	66	8.5	0.08	2.55	0.13
Guyuk	Lakumna	20-200	1.77	0.90	25	23	52	7.3	0.10	1.59	0.65
Hong	Dulmava	27-201	1.82	0.51	67	15	18	7.5	0.06	1.03	0.17
Hong	Hushere-Zum	41-205	1.93	0.46	80	8	12	6.3	0.03	2.41	0.40
Numan	Bare	25-200	1.62	0.35	74	9	17	6.6	0.02	4.07	0.20
Numan	Kikan_Kodomti	22-200	1.76	0.66	71	9	20	7.3	0.04	13.7	0.20
Shelleng	Lakati-Libbo	27-200	1.83	0.30	78	9	13	7.4	0.01	5.04	0.20
Shelleng	Jonkolo-Lama	15-200	2.06	0.33	78	10	12	5.9	0.02	0.89	0.14
Song	Sabon-Gari	31-200	1.73	0.66	25	33	42	6.2	0.04	1.45	0.4
Song	Suktu	35-210	2.08	0.22	71	11	18	6.3	0.03	6.56	0.20
Yola North	Yelwa-Jambore	24-155	2.19	0.4	77	11	12	6.5	0.03	1.8	0.09
Yola South	Fufore	20-145	1.98	0.54	65	17	18	9.0	0.02	32.1	0.10

***BD**=bulk density, **OC**=organic carbon content, **N**= percentage of Nitrogen and **P**=Available Phosphorus*

Table 2.3. Subsurface physical and chemical properties used for model applications in Borno State.

Location		Profile depth	BD	OC	Sand	Silt	Clay	pH	N	Meh. P	K
LGA	Community	(cm)	(g/cm^3)	(%)	(%)	(%)	(%)	(H_20)	(%)	(ppm)	cmol/kg
Bayo	Balbaya	9-200	1.59	0.29	83	7	10	6.1	0.01	1.03	0
Bayo	Briyel	15-200	1.32	0.39	19	29	52	8.4	0.02	2.69	0.4
Bayo	Jara-Dali	8-200	1.55	0.33	51	13	36	6.6	0.02	1.72	0.3
Biu	Buratai	29-150	1.63	0.17	74	8	18	7.6	0.02	2.69	0.6
Biu	Kabura,	22-101	1.36	0.78	36	38	26	7.1	0.06	0.89	9
Biu	Mathau	12.0-94	1.62	0.12	90	0	10	7.4	0	2.83	0.8
Biu	Tum	12-200	1.4	0.19	28	24	48	7.4	0.01	1.17	0.6
Hawul	Kwajaffa	30-110	1.31	0.54	16	27	57	7.4	0.06	2.28	0.7
Hawul	Puba Vidau	10-200	1.32	0.4	18	19	63	8.3	0.02	0.89	0.6
Hawul	Sakwa Hema	15-170	1.57	0.52	74	9	17	7	0.04	0.76	0.1
Kwayakusar	Bila Gusi	80-200	1.59	0.48	67	15	18	6.5	0.02	2.14	0.1
Kwayakusar	Kurba Gayi	10-200	1.6	0.32	75	9	16	7.2	0.01	1.03	0.1
Shani	Gwaskara	19-200	1.57	0.34	72	13	15	7.1	0.01	11.5	0.1
Shani	Kubo	33-200	1.54	o.46	64	13	23	7.3	0.02	1.31	0.8
Shani	Lakundum	16-200	1.52	0.73	72	10	18	7.3	0.07	13.6	9

BD=*bulk density,* ***OC****=organic carbon content,* ***N****= percentage of Nitrogen and* ***P****=Available Phosphorus*

2.3 Weather

2.3.1. Methodology

Long-term weather data was sourced from gridded downscaled Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) for daily rainfall (Funk *et al.*, 2015) and National Aeronautics and Space Administration (NASA) database for Climatology Resource for Agroclimatology http://power.larc.nasa.gov/ that include minimum and maximum air temperature and solar radiation. CHIRPS produced satellite-based rainfall products with relatively high resolutions (5.5 km) and quasi-global coverage (50 ^{o}S- 50 ^{o}N) for daily, pentadal, and monthly precipitation. The data/parameters in NASA power are provided on a global grid with a spatial resolution of 0.5° latitude by 0.5° longitude. Thereafter, the two datasets were merged using R scripts were developed to append CHIRPS and NASA power data together and convert each location into a format readily ingestible by the APSIM model for the 33 selected sites.

2.3.2 Results

The long-term climatic condition of the selected communities/LGAs in both States is typical of the savannah agroecologies with three seasons, a hot and humid season from June to October during which crops are cultivated, a dry and cool season from November to February, and a dry and hot season from March to May (Dingkuhn et al., 2008). The long-term (1985-2017) rainfall indicates the rainy season starts in May and ends in October with the highest peak observed in the month August (Table 4 and 5). The results further reveal about 50 - 60% of seasonal rainfall were observed in the month of July and August and indicates high inter-seasonal variability (CV) ranging from 18 to 23 %. All the sites showed a distinct mono-modal rainfall pattern and warming temperature throughout the year. However, Fig. 2 and 3 showed that maximum temperature was faster decreasing into the growing season than minimum temperature. Also, there was no significant inter-annual variability observed among the sites for both temperatures, but maximum temperature indicated higher values (CV) varing from 3.0 to 3.7% than minimum temperature ranged from 2.0 to 2.3 in both states.

In Adamawa State, the annual seasonal rainfall for most sites over the 33-year period (1985-2017) ranged from 868–893 mm, meanwhile Dulmava, and Hushere Zum in Hong LGA, and Guyaku and Tawa, Gombi LGA observed higher seasonal rainfall between 1042 and 1104 mm (Table 4). The average monthly maximum temperature across the sites over the climatic period ranged between 27.5 and 39.1 ^{o}C (Fig. 2a), while average monthly minimum temperature ranged from 15.8 to 24.9 ^{o}C (Fig. 2b). Similarly, in Borno State, the annual seasonal rainfall for most sites over the 33-year period (1985-2017) ranged from 883–998 mm (Table 5). Average monthly maximum temperature across the sites over the climatic period ranged between 27.8 and 38.9 ^{o}C (Fig. 3a) while average monthly minimum temperature ranged from 15.5 to 24.7 ^{o}C (Fig. 3b). For minimum temperature trend, the lowest value is observed in January, which coincided with a dry and cool season between November and February, while the highest value was observed in April indicating the hottest period of the year. The lowest maximum temperature was observed in August which coincided with the peak of rainy season in both states while the highest maximum temperature was observed in March coincided with the hottest month of the year occur between March and May.

Table 2.4 Variability analyses of monthly and seasonal rainfall in the simulation sites in Adamawa State from 1985 to 2017.

Annual*-total seasonal rainfall from May-Oct;* ***Stdev****- Standard deviation from mean;* ***CV****- coefficient of variation in percentage*

LGA	Community	May	Jun	Jul	Aug	Sep	Oct	Annual	Stdev	C.V (%)
Demsa	Demsa-Nassarawo	102.1	121.2	189.3	234.3	172.7	73.5	893	188	21
Demsa	Mbula Kuli	95.9	115.7	186.5	225.8	168.1	58.6	851	181	21
Girei	Daneyel	99.8	118.1	202.9	240.5	156.9	54.4	873	191	22
Girie	Woroshi	103.3	126.4	216.5	244	156.4	55.7	902	191	21
Gombi	Guyaku	117.9	155.9	228.9	308.8	176.6	99.1	1087	230	21
Gombi	Tawa	134.2	149.6	237.1	293.3	192.4	97.2	1104	239	22
Guyuk	Lakumna	91.8	110.3	167.5	258.2	174.9	68.9	872	185	21
Guyuk	Chikila	98.5	106.5	178.4	249.7	165.2	67.8	866	186	21
Hong	ushereZum	120	133.8	211.7	266.5	196.7	113	1042	241	23
Hong	Dulmava	109.9	150.6	225.5	302.8	202.2	113.1	1104	247	22
Numan	Bare	91.9	107.4	176.9	244.2	162.9	80.6	864	194	22
Numan	Kodomti	91.1	109.5	176.8	243.2	170.2	75	866	194	22
Shelleng	Lakati-Libbo	95.2	109.6	186.8	250.2	155.2	74.9	872	191	22
Shelleng	Jonkolo-Lama	97.6	115	182.4	268.6	166.2	73.1	903	197	22
Song	Sabon-Gari	99.8	119.5	211.3	269.7	181.8	82.1	964	212	22
Song	Suktu	99.6	116.3	211.4	256.5	157.8	61.5	903	199	22
Yola North	Yelwa-Jambore	102.1	125.4	206.6	218	163.5	52.2	868	189	22
Yola South	Fufore	103.8	140.6	220.6	218.5	160.5	51.4	895	190	21

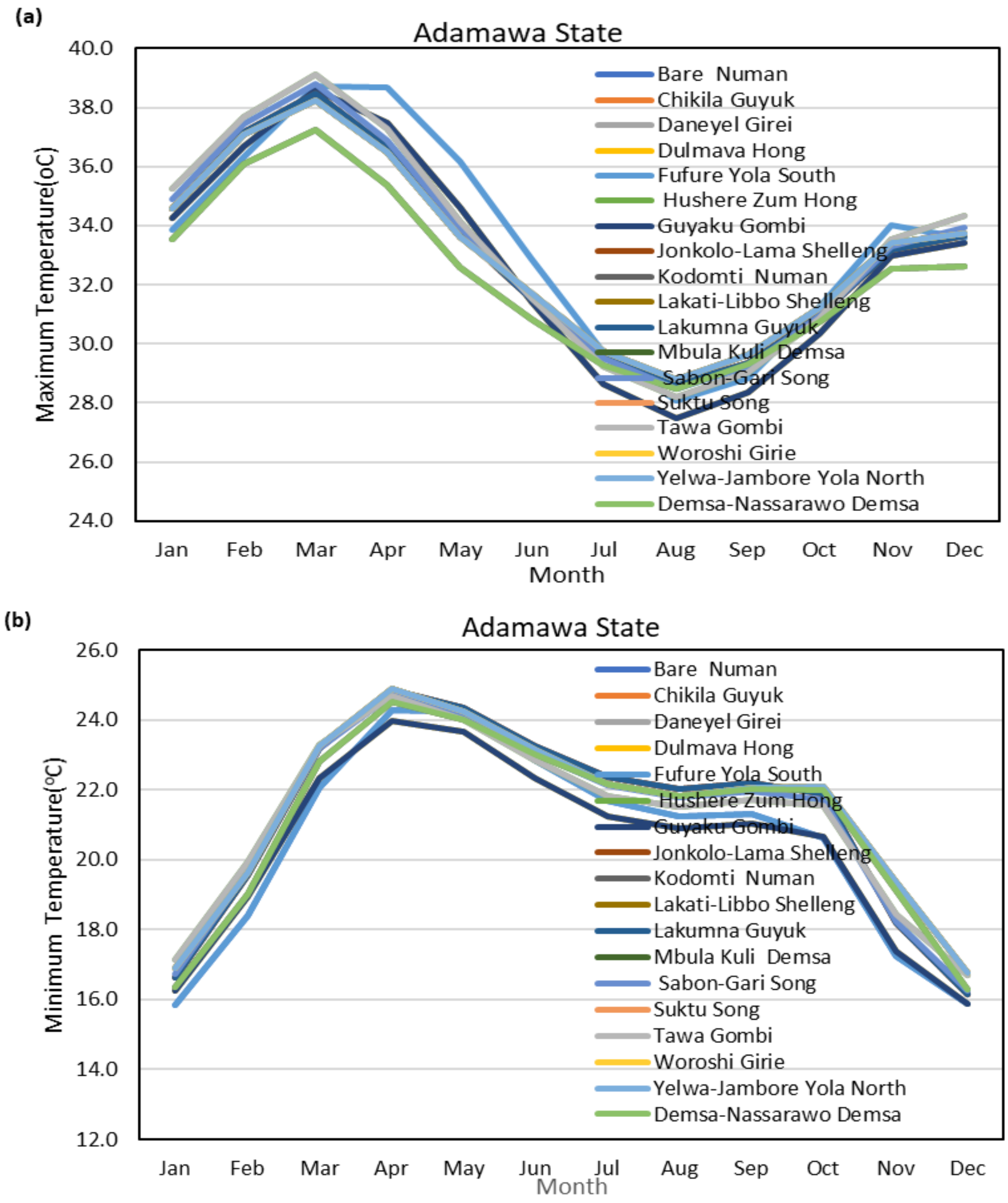


Fig. 2.2a &b: Average monthly variations of Maximum and Minimum temperatures between 1985 and 2017 across the simulation sites in Adamawa State. The coefficients of variation (CV) ranged from 3.0-3.7% for maximum temperature and 2.0-2.3% for minimum temperature.

Table 2.5 Variability analyses of monthly and seasonal rainfall in the simulation sites in Borno State from 1985 to 2017.

LGA	Community	May	Jun	Jul	Aug	Sep	Oct	Annual	Stdev	C.V (%)
Bayo	Balbaya	87.9	141.3	202.9	287.9	167.4	67.4	955	206	22
Bayo	Briyel	93.2	129	174.2	242.7	182.7	61.1	883	182	21
Bayo	Jara-Dali	78.4	136.8	202.8	289	204.4	80.3	992	217	21
Biu	Kabura	72.5	142.4	209.7	316.1	149.3	48.4	939	188	20
Biu	Mathau	78.3	144.4	204.4	312.1	165.6	51.9	957	174	18
Biu	Tum	86.2	149.8	218.1	317.4	170	56.9	998	204	20
Biu	Buratai	77.4	144.3	210.9	318.4	148.5	45.6	945	191	20
Hawul	Kwajaffa	99.7	142.3	204.3	306.7	179.3	51.2	983	186	19
Hawul	Puba Vidau	96.6	144.2	199.6	299.8	188.3	60.3	989	191	19
Hawul	Sakwa Hema	93.3	144.2	206.9	307.4	176.8	60.2	989	186	19
KwayaKusar	Bila-Gusi	98.9	124.5	190.6	268.6	183.4	75.7	942	189	20
Kwayakusar	Kurba Gayi	85.5	145.9	213.1	303.1	166.2	61.1	975	199	20
Shani	Gwaskara	83.5	142.1	198.5	295.4	201.6	74.9	996	192	19
Shani	Kubo	97.3	121.6	181.9	262.2	192.2	72.3	927	186	20
Shani	Lakundum	85.2	146	220.2	307.1	158.2	77.9	995	213	20

Annual*-total seasonal rainfall from May-Oct;* ***Stdev****- Standard deviation from mean;* ***CV****- coefficient of variation in percentage*

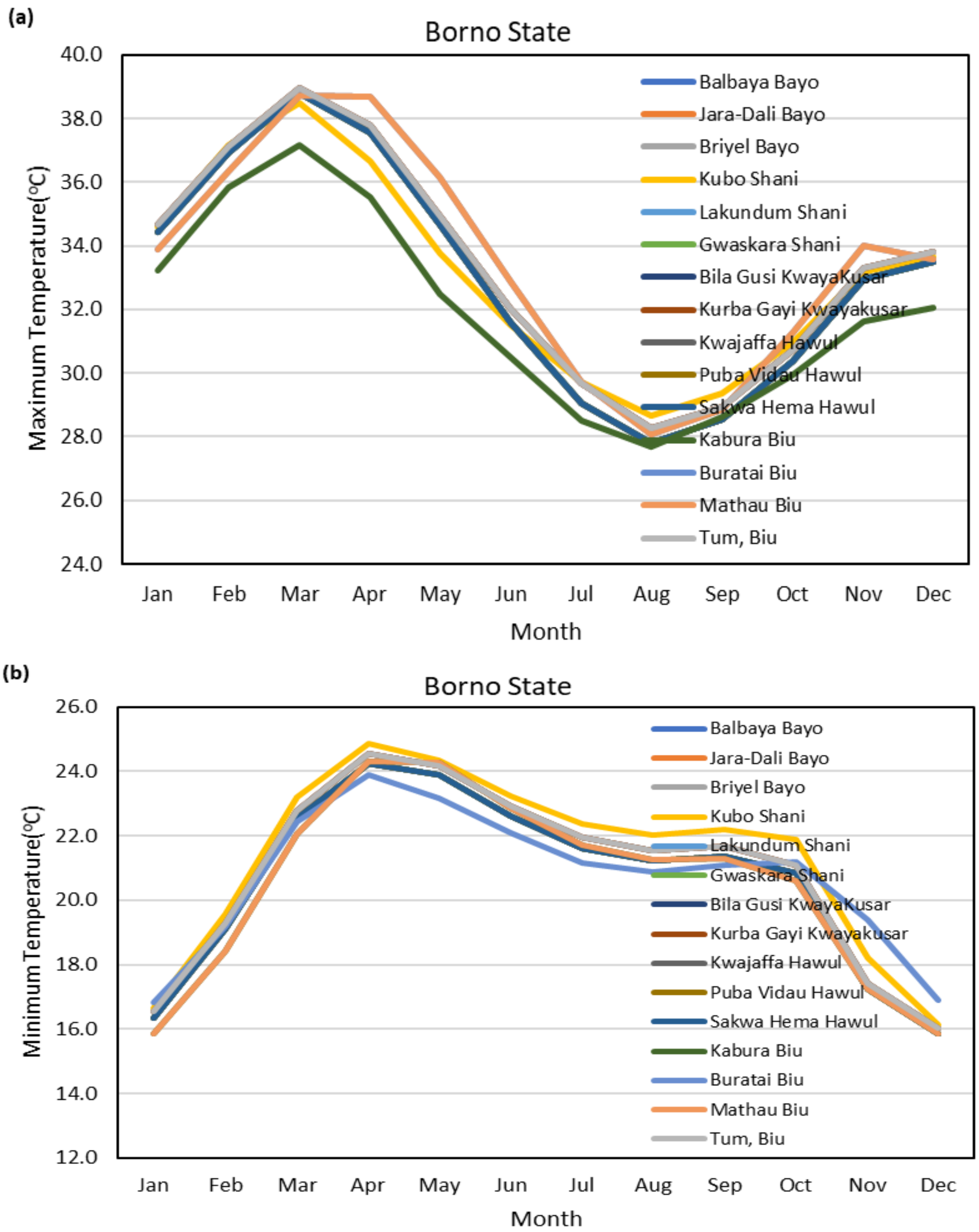


Fig. 2.3a &b Average monthly variations of Maximum and Minimum temperatures between 1985 and 2017 across the simulation sites in Borno State. The coefficients of variation (CV) ranged from 3.0-3.7% for maximum temperature and 2.0-2.3% for minimum temperature.

References

Adnan, A.A., Jibrin M.J., Kamara, A.Y. Abdulrahman, B.L., Shuaibu A.S., and Garba, I.I. (2017). CERES-Maize Model for Determining the Optimum Planting Dates of Early Maturing Maize Varieties in Northern Nigeria. *Frontiers in Plant Science*, 8: 1118.

Atehnkeng, J., Ojiambo, P.S., Donner, M., Ikotun, T., Sikora, R.A., Cotty, P.J., and Bandyopadhyay, R. (2008). Distribution and toxigenicity of *Aspergillus* species isolated from maize kernels from three agro-ecological zones in Nigeria. *International Journal of Food and Microbiology*, 122: 74–84.

Ayanlade, A. (2016). Seasonality in the daytime and night-time intensity of land surface temperature in a tropical city area. *Science of the total Environment*, *557*, pp. 415-424. Doi: 10.1016/j.scitotenv.2016.03.027.

Bray, R.H., and Kurtz, L.T. (1945). Determination of total, organic, and available forms of phosphorus in soils. *Soil Science*, 59: 39-45.

Bremmer, J.M. (1996). Nitrogen-Total. In: D. L. Sparks. *Method of Soil Analysis Part 3* - Chemical Methods, SSSA Book Series 5, Madison, Wisconsin, USA. Pp. 1085 - 1122.

Dingkuhn, M., Kouressy, M., Vaksmann, M., Clerget, B., Chantereau, J., 2008. A model of sorghum photoperiodism using the concept of threshold-lowering during prolonged appetence. *European Journal of Agronomy*, 28, 74–89.

FAO (2006). Base Reference Base for Soil Resources. A framework for international classification, correlation and communication. World Soil Resources Reports 103, FAO, Rome. 145 pp.

FAO–UNESCO (1974). Soil map of the world. Vol. I-legend. Paris. 59 pp.

Funk, C., Peterson, P., Landsfeld, M. et al. *(2015).* The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. *Sci Data* **2,** 150066. https://doi.org/10.1038/sdata.2015.66.

Gee, G.W., and Or, D., (2002). Particle-size analysis. *Methods of Soil Analysis* Part 4. Physical Methods SSSA Book Series, 255-293. doi:10.2136/sssabookser5.4.c12.

Heanes, D.L. (1984). Determination of total organic-C in soils by an improved chromic acid digestion and spectrophotometric procedure. Commun. Soil Sci. Plant Anal. 15:1191-1213.

Jagtap, S.S., (1995). Changes in Annual, Seasonal and Monthly Rainfall in Nigeria during 1961-1990 and Consequences to Agriculture. *Discovery and Innovation*, 7 (4): 311-426.

Mehlich, A. (1984). Mehlich 3 Soil Test Extractant: A Modification of Mehlich 2 Extractant. *Comm. Soil Sci. Plant Anal*. 15 (12): 1409–1416.

Omotosho, J. B., Agele, S.O., Balogun, I.A. and Adefisan, E.A. (2013). Climate variability, crop-climate modeling and water ecophysiology research: implications for plant's capacities for stress acclimation, yield production and food security. *Global Journal of Plant Ecophysiology*, **3**(2), 56–69.

Chapter 3

Using the DSSAT Model to simulate the performance of maize, cowpea, and soybean in Adamawa and Borno States

Abstract

Cropping system simulation models present an important opportunity for extrapolating short-duration field experimental results to other years and locations using long-term weather and soil information. To make recommendations for suitable crop varieties in Adamawa and Borno States, we calibrated and validated the CERES-maize, CROPGRO-soybean, and CROPGRO-cowpea models using secondary data collected from northern Nigeria. A close agreement was obtained between simulated and observed values with a low RMSE and a high *d* index for all measured parameters for all crops. After confirming the credibility of the three models, sensitivity analyses were carried out to test the performance of some selected improved cowpea, maize, and soybean varieties. For each crop, a 30-year sensitivity analysis was conducted in 15 communities in Borno and 18 communities in Adamawa, in northeast Nigeria, using the DSSAT model. For maize, the sensitivity analysis showed that medium-maturing and drought-tolerant (IWD C2 W and DT STR W) produced grain yields that were 20 and 25% higher than those of TZL COMP1 Syn W and 99 EVDT, respectively. The variety DT STR W produced grain yields that were 15 and 18% higher than that of TZL COMP 1 Syn W in Adamawa and Borno, respectively, while the increase was 20% over that of 99 EVDT in both locations. For soybean, the variety TGX1951-3F produced the highest grain yield in both States, while TGX1448-2E produced the lowest grain yield. The variety TGX1951-3F produced grain yields that were 20, 23, 17, and 8% higher than that of TGX1448-2E, TGX1835-10E, TGX1987-10F, and TGX1904-3F, respectively, in Adamawa. The yields were higher by 21, 17, 13, and 9% for the same varieties in Borno. For cowpea, the simulation results showed that the medium-maturing *Striga*-resistant variety (IT99K-573-1-1) recorded the highest grain yield of above 1 ton ha^{-1} in both States. The highest grain yield of 1116 kg ha^{-1} was simulated at Mathau in Biu Local Government Area (LGA)while the lowest grain yield of 960 kg ha^{-1} was simulated at Bila Gusi in Kwayakusar LGA in Borno State. In Adamawa State, the highest grain yield of 1101 kg ha^{-1} was simulated at Guyaku in Gombi LGA while the lowest grain yield of 731 kg ha^{-1} was simulated at Yola North. The models simulated higher grain yields for all the crops in Borno than in Adamawa State. We concluded that the CERES and CROPGRO models can accurately predict the performance of grain crop varieties in the two States. The maize varieties IWD C2 W and DT STR W; soybean varieties TGX1951-3F and TGX1904-6F; and *Striga*-resistant cowpea varieties IT99K-573-1-1 and UAM 09 1051-1 can be recommended for production and dissemination in the study areas of the two States.

3.1. Introduction

Maize, cowpea, and soybean are among the major and important staple and cash crops in Nigeria. Maize (*Zea mays* L.) is a very important cereal crop and is grown in virtually all the geo-ecological zones of Nigeria. Maize is most productive in the middle and the northern belts of Nigeria where sunshine is adequate, and rainfall is moderate. The lowland humid forest zone which is characterized by high rainfall and humidity is not particularly suitable for maize production due to the high incidence of the pest and diseases, low light intensity during the growing season and low soil fertility. The recent achievements by breeders in the development and release of superior varieties of maize with higher yield potential and better resistance to insect pests and diseases play a central role in increasing maize production in Nigeria. Nigeria is currently the 9th largest producer of maize in the world and the 2nd largest producer in Africa after South Africa. The total annual national production has increased from 658,000 MT in 1978 to about 10,155,027 MT in 2018 (FAOSTAT, 2018).

Cowpea (*Vigna unguiculata* L. Walp) is the most important grain legume crop in Nigeria. It is widely cultivated for food and its seed is the major source of high-quality plant protein in human diet. The seed protein content ranges between 23% and 30% and contain most of the essential amino acids. Nigeria is the largest cowpea producer in the world with an annual production of 2.2 million tonnes from about 4 million hectares (FAOSTAT, 2018). Soybean (*Glycine max* L.) is becoming a major food and cash crop due to its high cash value and relative ease of cultivation and is widely used in the food and feed industry. Soybean is the world's leading source of oil and protein. It has the highest protein content of all food crops and is second to groundnut in terms of oil content among food legumes. It contains high protein content and high-quality oil of about 40% and 20%, respectively. It contributes to improving soil fertility by providing biologically fixed nitrogen, increasing soil organic matter and is used in crop rotation to reduce *Striga* infestation on farmers' fields. Nigerian soybean production is rising steadily spurred by favourable grower price and sustained high demand for soybean by products over the past years. Nigeria soybean domestic outputs has increased to about 758,033 MT in 2018 (FAOSTAT, 2018).

Despite being one of the leading producers of cowpea, maize and soybean, Nigeria's demand for these commodities exceeds its supply and the deficit is met by imports from neighbouring countries. With the increase in Nigeria's population from the current approximate population of 170 million to 310 million by 2050 (UNDESA/PD, 2015), the demand is going to increase even further. This is due to the facts that the average yields for cowpea, maize and soybean are quite low compared to other developed countries and even the world average. The major limiting factors to potential production in Nigeria include climate variability (especially drought and high temperature), low soil nutrient level particularly nitrogen and phosphorus, infestation by parasitic weeds such as *Striga* and *Alectra*. Other limitations to high production include poor management practices such as inappropriate sowing time, limited use of inputs especially fertilizer and improved seeds. Therefore, improving and sustaining crop productivity is a critical need in Nigeria and this will mostly occur in the Sudan and Guinea savannah regions where yield potential is much higher than in the forest due to low solar radiation and high humidity.

To address these constraints and improve crop production in Nigeria, international researchers in collaboration with national partners have developed improved crop varieties that are tolerance to drought, heat stress, pest and diseases (Menkir et al., 2006, 2007; Badu-Apraku et al., 2013, 2016; Omoigui et al., 2018; Kamara et al. 2004; Kamara, 2017). In addition, complementary agronomic management practices such as right fertilizer, optimum fertilizer rates and sowing windows have been developed and evaluated in the region to increase yields of the improved varieties on farmers' fields. Dissemination of these technologies to farmers is being channelled through field testing and demonstrations, provision of advisory services on crop management and storage, and through the organization of farmers' field schools, field days and radio shows.

A project, Integrated Agriculture Activity funded by the USAID in northeast Nigeria seeks to disseminate improved crop varieties and complementary technologies in Adamawa and Borno States. This would require information on the most suitable crop varieties for targeted Local Government Areas (LGAs) in the States. To provide such information would require testing these varieties in combination with a range of improved crop production technologies across several locations and LGAs. However, these traditional methods of technology dissemination have some limitations. Reports on the performance of technologies are largely site specific and do not take into consideration variability in soils and climate conditions outside the areas where the technologies are tested (Adnan et al. 2020, Tofa et al., 2020). To assess the performance of these technologies on a large scale would require time consuming and expensive large-scale experiments across crop growing regions like the savannas in northern Nigeria.

An alternative to address these limitations is the use of crop models that simulate crop yield under different soil and climate conditions. Cropping system simulation models such as; Crop Environment Resource Synthesis (CERES) Maize, SOYGRO-soybean, and CROPGRO in Decision Support System for Agricultural Technology Transfer (DSSAT) present very important opportunity for extrapolating short-duration field experimental results to other years and other locations making use of long-term weather and soil information (Hoogenboom et al., 2017). DSSAT has been tested and evaluated extensively by many researchers across locations and found good correlations between observed and simulated values for a wide range of experimental practices against field data and environmental conditions (Banterng et al., 2010; Jibrin et al., 2012; Adnan et al. 2020; Tofa et al., 2020). To be able to make site-specific recommendations for suitable crop varieties and crop management practices in Adamawa and Borno States, we calibrated and validated the CERES-maize, SOYGRO-soybean and CROPGRO models using secondary data collected from northern Nigeria and used the results to simulate the performance of the varieties of cowpeas, maize, and soybean (Table 1).

Table 3.1 Source and description of crop varieties used in the study.

Crop	Variety	Source	Maturity (days)	Seed Colour	Characteristics	Yield potential
Maize						
	99 EVDT STR	IITA	90-95	white	tolerant to drought and resistant to *Striga hermonthica*	4.5 t/ha
	IWD C2 W	IITA	106-110	white	Tolerance to drought stress and *Striga* infestation	6.9 t/ha
	TZL COMP 1 SYN	IITA	110-120	white	Non-drought tolerant but *Striga* infestation	6.4 t/ha
	DT STR W	IITA	95-100	white	Tolerance to drought stress, low soil N and *Striga* infestation	5.5 t/ha
Soybean						
	TGX1835-10E	IITA	80-90	cream	Non shattering	1.5 t/ha
	TGX1987-62F	IITA	80-90	cream	Shatters	2.0 t/ha
	TGX1951-3F	IITA	95-100	cream	Non shattering	3.0 t/ha
	TGX1448-2E	IITA	110-120	cream	Non shattering	2.5 t/ha
	TGX1904-6F	IITA	105-110	cream	Non shattering	3.0 t/ha
Cowpea						
	IT99K-573-1-1	IITA	70-75	white	Resistant to *Striga*	2.6 t/ha
	IT90K-277-2	IITA	75-85	white	Susceptible to *Striga*	2.7 t/ha
	UAM09 1051-1	UAM	75-85	brown	Resistant to *Striga*	2.0 t/ha

3.2. Calibration, evaluation and application of the Ceres-Maize Model in DSSAT to simulate performance of maize in selected communities in Adamawa and Borno States

3.2.1. Methodology

3.2.1.1. Model calibration

The main objective of model calibration was to adapt the model parameters to local environmental conditions (e.g. soil types and weather conditions) and crop cultivars so as to gain a good overall agreement between simulated and observed values. Calibration trials for maize were established under optimum conditions in diverse locations in Northern Nigeria from 2017 to 2019 cropping seasons to generate genetic coefficients of diverse maize varieties. Four maize varieties (99 EVDT, IWD C2 W, TZL COMP1 SYN and DT STR W) were planted between 1st and 2nd week of July. The maize calibration trials were established in 3 locations; Samaru Zaria in the northern Guinea savanna, Bayero University, Kano and Audu Bako Collage of Agricultural (ABCOA), Danbatta both in the Sudan savanna ecology). The varieties included both early and medium maturing varieties based on their superior agronomic performance and adaptations to biotic and abioticfactors. Soil samples were collected from the calibration site and analysed for nutrient content. Information on weather at the experimental sites were obtained from WatchDog weather stations installed at the sites.

For model calibration, the DSSAT crop model requires genotype specific parameters (GSPs), which are specific for each cultivar. GSPs allow the model to simulate the performance of diverse varieties under different soil, weather and management conditions (Hunt et al., 1993). GSPs of the maize varieties were first calibrated by adjusting the six coefficients P1, P2, P5, G2, G3, and phyllochron interval (PHINT) which describe the growth and development characteristics for each individual variety. Three parameters (P1, P2 and P5) define the life cycle development characteristics, two coefficients (G2 and G3) define growth and yield characteristics and one coefficient, PHINT, defines leaf tip appearances (Jones et al., 1986). Development coefficients are calculated in degree days (or thermal time) in the CERES-Maize. Thermal time in any given day is equal to mean air temperature minus base temperature (Ritchie et al., 1998).

$$\text{GDD} = \frac{Tmax + Tmin}{2} - Tbase$$

where GDD is growing degree days, Tmax is maximum temperature, Tmin is minimum temperature and Tbase is base temperature (Tbase for maize = 8 °C). GDD is cumulative and is measured in °C day^{-1}.

In the CERES-Maize model, the GSPs were calibrated by comparing simulated and measured data for days to anthesis, days to maturity, biomass, and grain yield from the calibration experiments. Since all the varieties are not in DSSAT, we created them in the genetic file (MZCER047.CUL) of DSSAT-CSM. Initial values of the GSPs were obtained from the generic early season cultivar (990001 EARLY SEASON) and generic medium season cultivar (990002 MEDIUM SEASON) for the medium maturing varieties, which were already available in the genotype files. The computed crop specific parameters values for the cultivars were copied into MZCER047.CUL file to operate the simulations. The Generalized Likelihood Uncertainty Estimation (GLUE) Coefficient Estimator module (He et al., 2010) fixed in the DSSAT model was used to estimate the GSPs for both maize varieties. The soil, weather, and crop management information were used to provide the environmental calibration for the model. For model calibration, water and nitrogen balance simulation controls were switched off, to ensure that no stress for water or nitrogen were simulated since near-optimal conditions were assumed for water and nitrogen in the calibration experiments.

3.2.1.2. Model validation

The calibrated coefficients were used for model validation. Validation is the making of comparison of model predictions with experimental data which have not been previously used for model development and calibration. The model was validated with field data sets collected from nitrogen experiments at various locations by comparing the observed and simulated results. The experiments were conducted in two years (2015 and 2016) and two locations (Samaru Zaria and Iburu). The data were used for model evaluation for IWD C2 W (SAMMAZ-15), DT STR W (SAMMAZ-26) and ZL Comp1 Syn (SAMMAZ-16) varieties using four levels of nitrogen (0, 60, 120 and 180 kg N ha^{-1}) application. For variety EVDT 99 W STR (SAMMAZ-27), independent data sets collected from mize N response to 5 levels of nitrogen (0, 30, 60, 90 and 120 kg N ha^{-1}) were used. These data were collected during 2016 and 2017 cropping seasons at Abuja and Samaru Zaria. Soil samples were collected from all experimental sites and analyzed for nutrient content. Weather data were collected from the WatchDog weather stations installed at all the sites. Model validation was done to test the parameters already optimized in the calibration exercise using independent experimental data. Information on soil and weather were used as input for model validation. Data used in model evaluation include final grain yield and shoot dry matter ha^{-1}. Model statistics used to evaluate model performance are root mean square error (RMSE) and *d*-statistic (Willmott *et al*., 1982).

$$\text{RMSE} = \sqrt{1}/N \sum (Oi - Pi)2$$

Where: P = predicted, O= observe, N= number of observations within each treatment.

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

Where: $S_i = S_i - \overline{m}$ and $m_i = m_i - \overline{m}$

The *d* statistic is recommended for making cross-comparisons when the *d* value is both relative and has bounded measures. According to the *d*-statistic, the closer the index value is to one, the better the agreement between the two variables that are being compared. Easy-grapher program in DSSAT was used to graph and compare simulated model outputs with observed data and also calculate model performance statistics.

3.2.1.3. Model application (Seasonal analysis)

After confirming the credibility of the model, sensitivity analysis was carried out to test the performance of some selected improve cowpea, maize and soybean varieties as presented in Table 1. The sensitivity analysis was conducted in 15 communities in Borno and 18 communities in Adamawa, in the northeast Nigeria, using the seasonal analysis tool of DSSAT. For maize scenario analysis, the sowing date was set at June 30 in all the locations at both States. A compound fertilizer (NPK 15:15:15) was used in the model to supply 60 kg each of N, P_2O_5 and K_2O ha^{-1} at 14 days after sowing (DAS) as first application. Urea (46 % N) was used to supply the remaining dose (60 kg N ha^{-1}) of nitrogen at 45 DAS. Generally, sowing was done at soil depth of 5 cm, with a sowing density of 5.3 plants per square meter.

3.2.2. Results

3.2.2.1. ***Model calibration***

The results for the model calibration experiments for maize varieties are presented in Figures 1-4. A close agreement was obtained between simulated and observed values for all four measured parameters. The statistical values of simulated and measured days to anthesis and physiological maturity ranged between (RMSE = 1.9 to 2.3 days) and (d-index = 0.82 to 0.97) for all varieties. The comparison between simulated and observed grain yield were also quite good for all the maize varieties. The RMSE values for grain yield ranged from 158 kg ha^{-1} for DT STR W to 470 kg ha^{-1} for IWD C2 W while d-index values were above 0.90 for all varieties except DT STR W that has 0.61. The predictions for shoot dry yields were also good all for all varieties; the RMSE values for shoot dry yield ranged from 483 kg ha^{-1} for 99 EVDT to 1727 kg ha^{-1} for IWD C2 W while d-index value ranged was between 0.80 and 0.88 for all varieties. Generally, the coefficients of determination (R^2) for the calibration of all the tested parameters for all varieties were good.

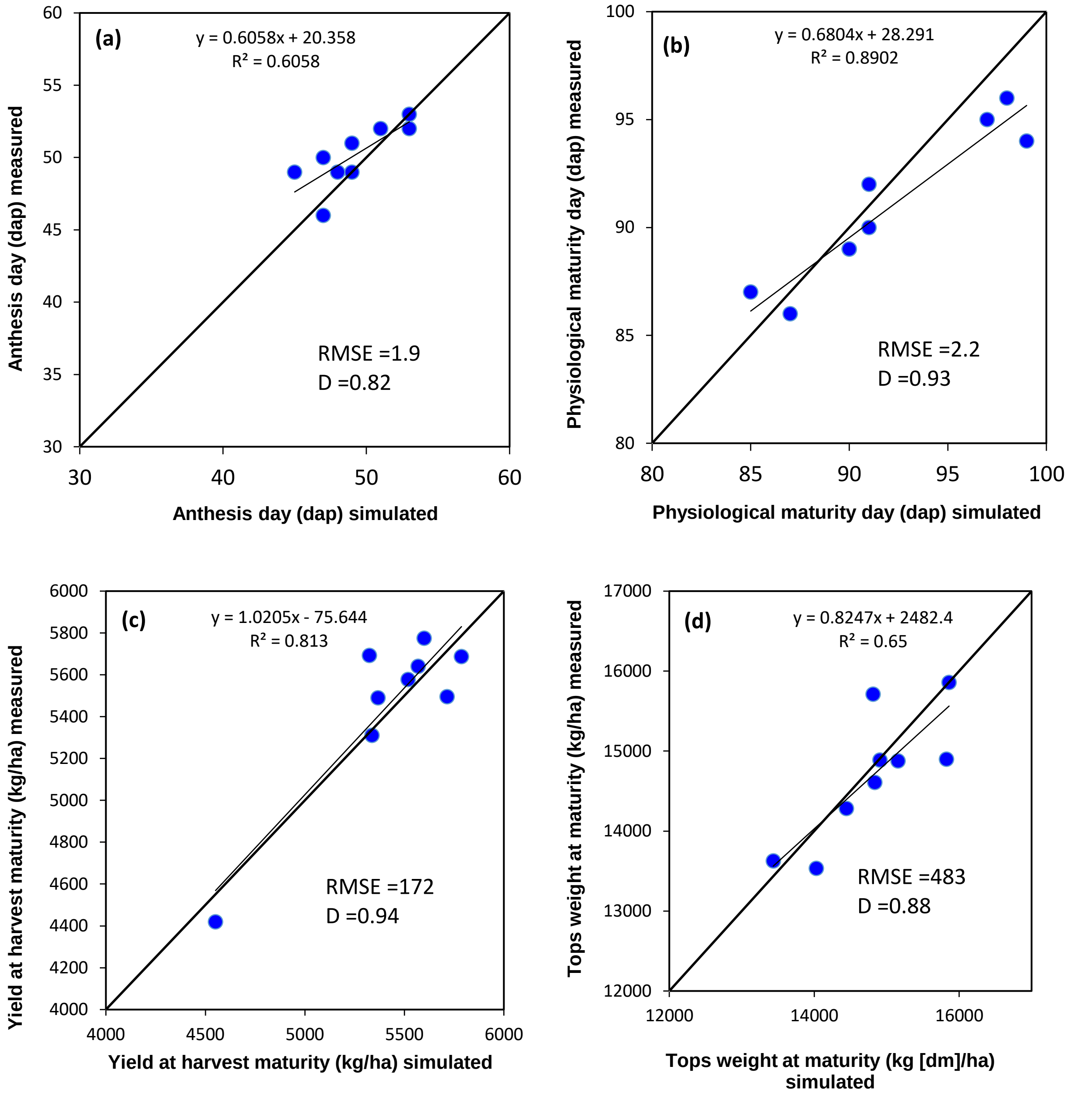


Fig. 3.1: Comparison of simulated and measured anthesis (a), physiological maturity (b), grain yield at maturity (c) and shoot dry weight (d) for 99 EVDT maize variety.

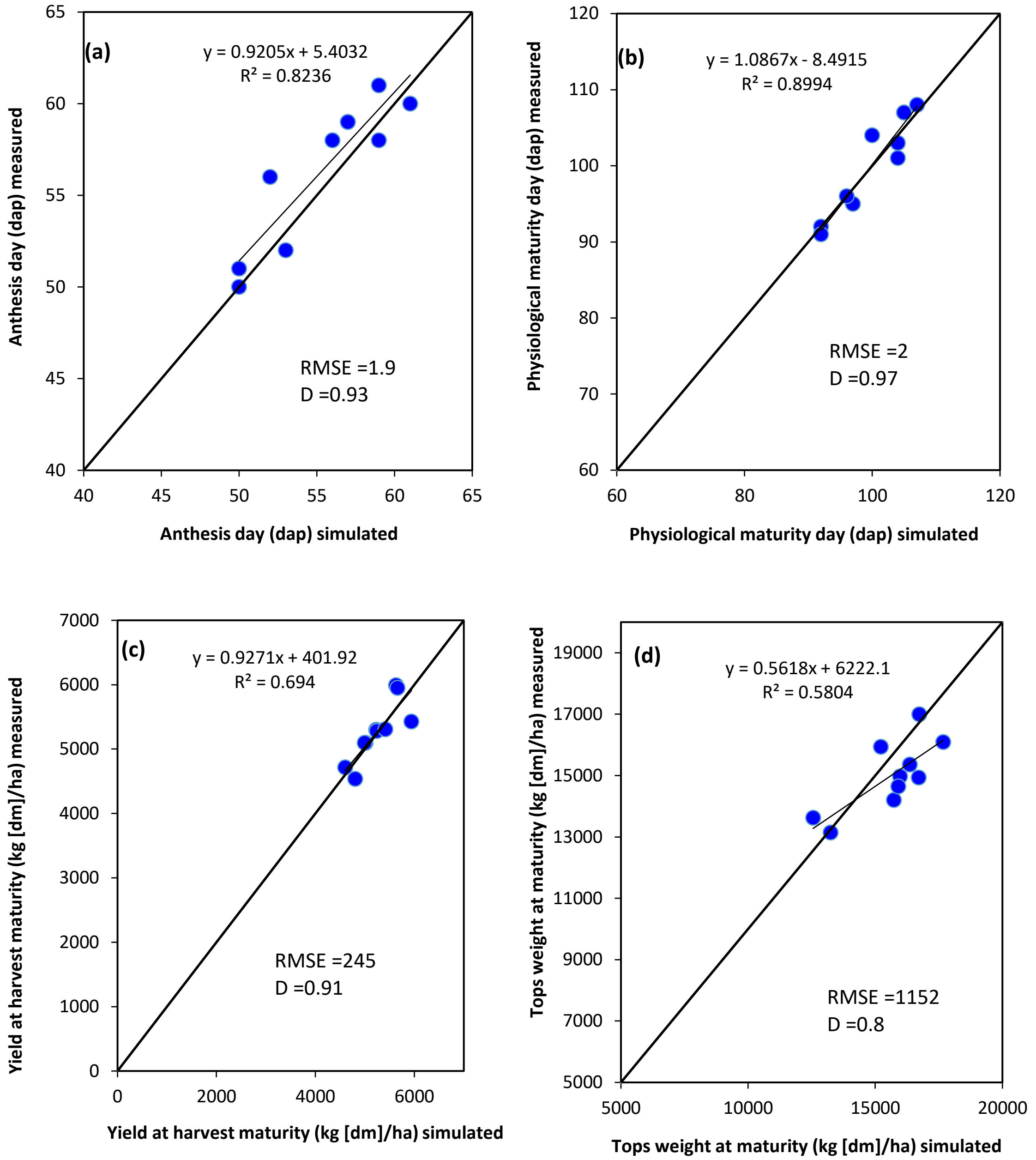


Fig. 3.2 Comparison of simulated and measured anthesis (a), physiological maturity (b), grain yield at maturity (c) and shoot dry weight (d) for TZL Comp1 Syn W maize variety.

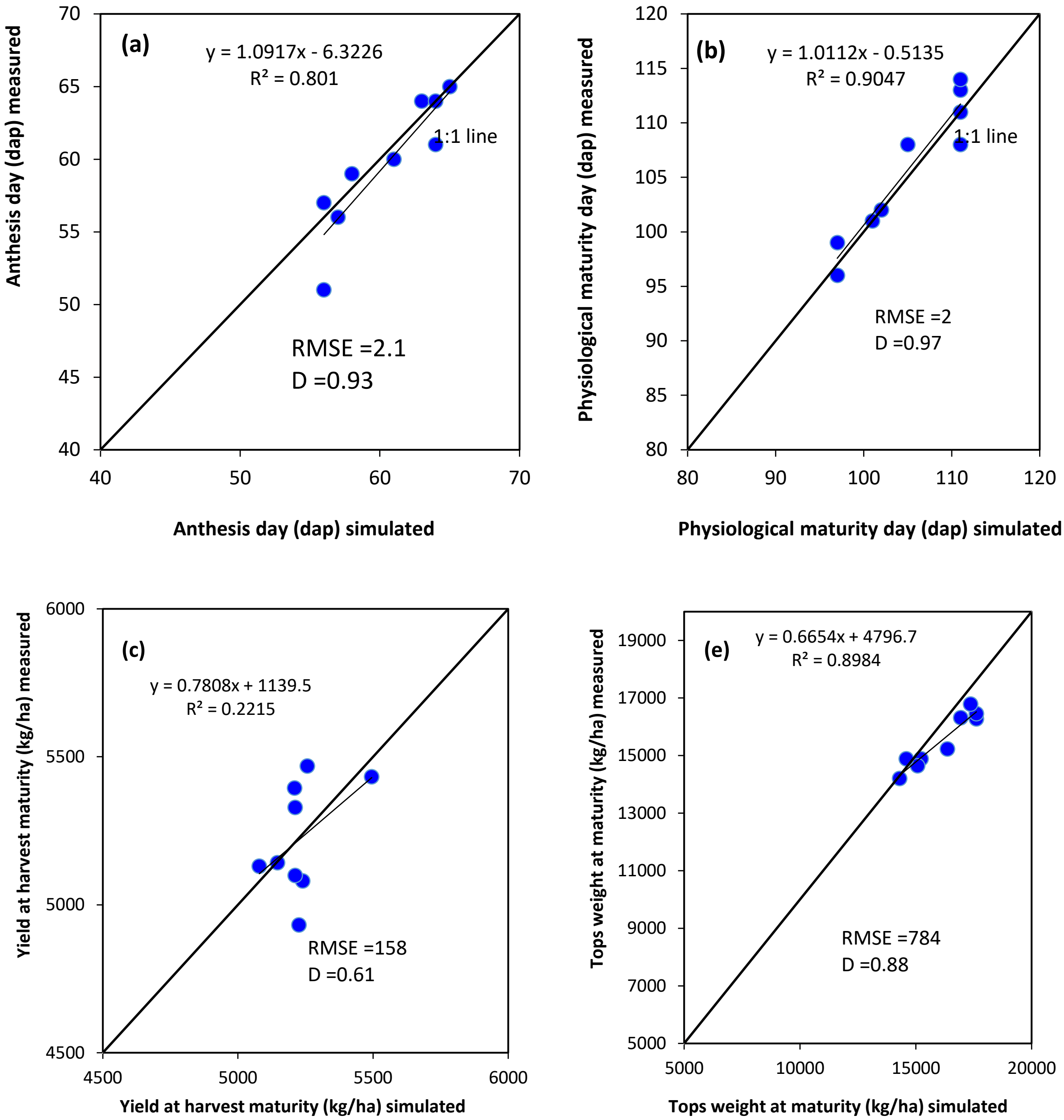


Fig. 3.3 Comparison of simulated and measured anthesis (a), physiological maturity (b), grain yield at maturity (c) and shoot dry weight (d) for DT STR W maize variety.

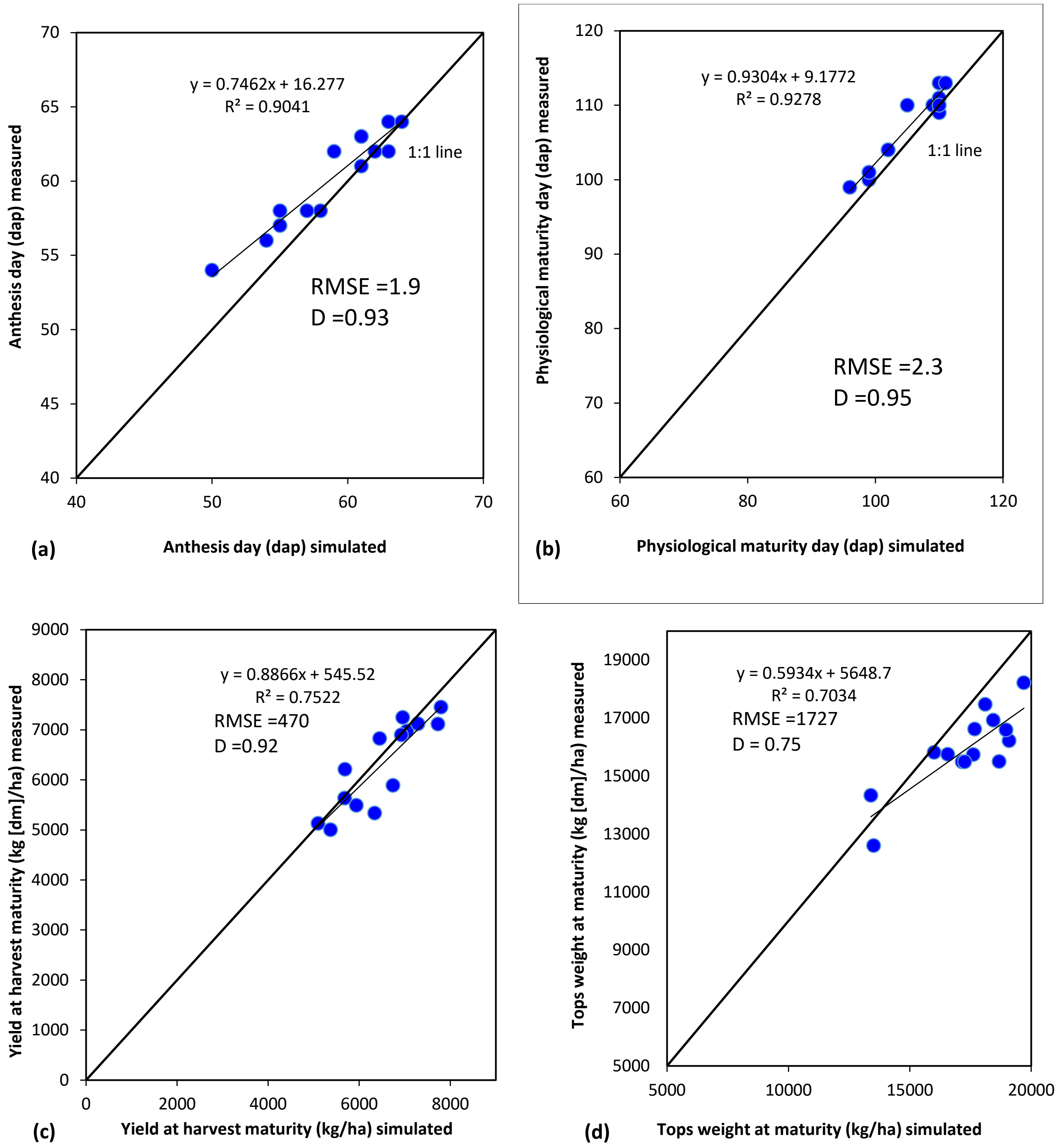


Fig. 3.4 Comparison of simulated and measured an thesis (a), physiological maturity (b), grain yield at maturity (c) and shoot dry weight (d) for IWD C2 W maize variety.

3.2.2.2. Model validation

The accuracy of the CERES-Maize model simulations and performance of genetic coefficients were assessed by running the model with independent data sets collected during 2015 and 2016 seasons for IWD C2 W, DT STR W and ZL Comp1 Syn using four levels of nitrogen (0, 60, 120 and 180 kg N ha^{-1}) application at Iburu and Zaria. For the variety 99 EVDT, independent data sets under 5 levels of nitrogen (0, 30, 60, 90 and 120 kg N ha^{-1}) application were used. The data were collected during 2016 and 2017 cropping seasons at Abuja and Samaru Zaria. Grain yield at maturity and shoot dry yield at maturity were used for model evaluation (Tables 2-4). The model's evaluation of grain yield was good at all N treatment levels for the four varieties in each location. In all the locations and years, the model slightly underestimated or overestimated the measured parameters for all the four maize varieties at various N levels. However, the under or over estimations were within the acceptable range of below 25 %. In all the locations there was a good fit in the model prediction of grain yield with low RMSE and high *d-index* values. The values of RMSE for the four varieties ranged from 584 to 745 kg ha^{-1}. In all cases, d-index values for grain yield were above 0.93 indicating that the model is robust and accurate in measuring grain yield. The overall RMSE for shoot yield ranged from 1746 to 2339 kg ha^{-1} with d-index values also above 0.9 for all the varieties.

Table 3.2 Simulated (S), observed (O) and simulated minus observed (S - O) of grain yield and shoot yield of IWD C2 W and DT STR W obtained from validation experiments conducted at two locations over a two-year period .

			IWD C2 W						DT STR W					
Location	Year	N rate ($kg\ ha^{-1}$)	Grain yield ($kg\ ha^{-1}$)			Shoot yield ($kg\ ha^{-1}$)			Grain yield ($kg\ ha^{-1}$)			Shoot yield ($kg\ ha^{-1}$)		
			S	**O**	**S - O**	**S**	**O**	**S - O**	**S**	**O**	**S - O**	**S**	**O**	**S - O**
Iburu	2015	0	363	433	-70	2529	2222	307	1121	1036	85	5284	5581	-297
		60	2822	2683	139	7896	6688	1208	2564	3756	-1192	8807	9456	-649
		120	5664	3996	1668	11805	9585	2220	3912	4263	-351	11970	11345	625
		180	6664	4844	1820	12196	11454	742	5388	4566	822	14596	12669	1927
	2016	0	284	614	-330	3792	1660	2132	309	1135	-826	1976	4979	-3003
		60	3094	3610	-516	8630	5859	2771	2933	3628	-695	9334	8831	503
		120	5352	5619	-267	14486	8659	5827	5465	5037	428	14787	12261	2526
		180	6125	5859	266	15296	10381	4915	6311	5931	380	17483	14864	2619
Samaru	2015	0	214	730	-516	4089	1614	2475	233	996	-763	957	4799	-3842
		60	3028	3680	-652	9972	6289	3683	2680	3640	-960	8129	10601	-2472
		120	5374	5503	-129	12363	8964	3399	4449	4868	-419	12573	12197	376
		180	5981	5361	620	12337	10261	2076	4979	5593	-614	14551	13893	658
	2016	0	506	734	-228	4167	2043	2124	491	675	-184	1814	3025	-1211
		60	2957	2770	187	9005	6505	2500	3275	4128	-853	9496	9402	94
		120	5378	5405	-27	13468	9096	4372	5883	5476	407	14986	12135	2851
		180	6018	5531	487	13645	10293	3352	6611	5309	1302	17158	14883	2275
RMSE					*709*			*2339*			*745*			*1990*
d value					*0.97*			*0.94*			*0.96*			*0.95*

D ***-Willmott index of agreement (Willmott, 1982) ranging from 0 to 1, 1being perfect agreement***

Table 3.3 Simulated (S), observed (O) and simulated minus observed (S - O) of grain yield and shoot yield of TZL Comp 1 Syn W obtained from validation experiments conducted at two locations over a two-year period.

			TZL Comp1 Syn					
Location	Year	N rate (kg ha^{-1})	Grain yield (kg ha^{-1})			Shoot yield (kg ha^{-1})		
			S	**O**	**S – O**	**S**	**O**	**S - O**
Iburu	2015	0	785	991	-206	4024	5051	-1027
		60	3226	2787	439	10578	7755	2823
		120	5302	3849	1453	15280	11006	4274
		180	5909	4348	1561	17374	13836	3538
	2016	0	273	530	-257	1858	2579	-721
		60	2738	2853	-115	8203	6988	1215
		120	4494	3730	764	12485	9637	2848
		180	5120	4232	888	14632	11537	3095
Samaru	2015	0	207	633	-426	1750	3772	-2022
		60	2784	3941	-1157	8903	9852	-949
		120	4651	4683	-32	13429	12255	1174
		180	5035	4751	284	14931	12707	2224
	2016	0	649	711	-62	3105	4226	-1121
		60	3184	4013	-829	10005	9621	384
		120	5045	5008	37	14418	10136	4282
		180	5430	5382	48	15890	12679	3211
RMSE					*730*			*2511*
d value					*0.96*			*0.92*

D- Willmott *index of agreement (Willmott, 1982) ranging from 0 to 1, 1being perfect agreement*

Table 3.4 Simulated (S), observed (O) and simulated minus observed (S - O) of grain yield and shoot yield of 99 EVDT obtained from validation experiments conducted at two locations over a two-year period.

Location	Year	N rate (kg ha^{-1})	Grain yield (kg ha^{-1})			Shoot yield (kg ha^{-1})		
			S	**O**	**S - O**	**S**	**O**	**S - O**
Abuja	2016	0	464	1253	-789	1566	3826	-2260
		30	1883	2336	-453	4980	4725	255
		60	2878	3159	-281	7387	6279	1108
		90	3419	4003	-584	8832	9098	-266
		120	3549	4165	-616	9320	9717	-397
	2017	0	1035	1435	-400	2832	4200	-1368
		30	3260	2448	812	7438	6236	1202
		60	4224	3608	616	9568	7112	2456
		90	4365	4161	204	9765	8636	1129
		120	4290	4361	-71	9517	9412	105
Samaru Zaria	2016	0	483	1391	-908	2005	4750	-2745
		30	2009	2475	-466	6310	5842	468
		60	3681	3390	291	9816	8060	1756
		90	4631	4110	521	12177	10454	1723
		120	5109	4276	833	13577	11148	2429
	2017	0	313	1435	-1122	1695	4133	-2438
		30	1891	2449	-558	5894	5931	-37
		60	3612	3608	4	9336	6754	2582
		90	4456	4161	295	11608	9153	2455
		120	4819	4361	458	12757	10439	2318
RMSE					*584*			*1746*
d value					*0.95*			*0.91*

D- Willmott index of agreement (Willmott, 1982) ranging from 0 to 1, 1being perfect agreement

3.2.2.3. Model application (Seasonal analysis)

Results of seasonal analysis for mean grain yields in different locations conducted by the DSSAT model over 30-year period are presented in Tables 5 and 6 for Borno and Adamawa, respectively. In the two States, the location had significant long-term effect on grain yield of all the varieties. On average, the varieties produced between 5 and 7% higher grain yield in Borno when compared with that of Adamawa State. However, the four maize varieties responded similarly in both Adamawa and Borno States. The medium maturing and drought tolerant (IWD C2 W and DT STR W) varieties produced grain yields (above 4 t/ha) that were higher than those of the medium maturing and drought sensitive (TZL COMP1 Syn W) variety and the early maturing and drought tolerant (99 EVDT) variety. In Both Adamawa and Borno, IWD C2 W produced grain yields which were 20 and 25% higher than those of TZL COMP1 Syn W and 99 EVDT, respectively. DT STR W produced grain yields that were 15 and 18% higher than that of TZL COMP 1 Syn W in Adamawa and Borno, respectively, while the increase was 20% higher than that of 99 EVDT in both locations. TZL COMP 1 Syn W and 99 EVDT did not significantly differ in grain yield in all the locations. For the two States, the two varieties IWD C2 W and DT STR W are recommended for production and dissemination. However, the yield produced by 99 EVDT is within the acceptable range for early maturing maize varieties in northern Nigeria. To adapt to varying weather conditions, this variety is also highly recommended particularly when rains are late or early cessation of rainfall is envisaged.

Table 3.5 Maize grain yield (kg ha^{-1}) results of 30 years (1985-2014) seasonal analysis in Borno, northeast Nigeria.

Location		IWD C2 W	DT STR W	TZL COMP1	99-EVDT	Mean
Bayo	Balbaya	4619	4333	3920	3913	**4196**
Bayo	Briyel	4749	4624	3980	3869	**4306**
Bayo	Jara-Dali	4841	4695	4057	3983	**4394**
Biu	Buratai	4711	4552	3937	3796	**4249**
Biu	Tum	4782	4597	4021	3960	**4340**
Biu	Kabura	4829	4697	4046	3930	**4376**
Biu	Mathau	4837	4707	4048	3929	**4380**
Hawul	Kwajaffa	1767	2051	1019	820	**1414**
Hawul	Puba Vidau	4511	4458	3772	3647	**4097**
Hawul	Sakwa Hema	4490	4441	3755	3624	**4078**
Kwayakusar	Bila Gusi	4330	4151	3587	3508	**3894**
Kwayakusar	Kurbo Gayi	4847	4707	4064	3991	**4402**
Shani	Gwaskara	4896	4809	4080	3969	**4439**
Shani	Kubo	4376	4230	3622	3533	**3940**
Shani	Lakundum	4894	4807	4079	3967	**4437**
Mean		**4498**	**4390**	**3732**	**3629**	

Table 3.6 Maize grain yield (kg ha^{-1}) results of 30 years (1985-2014) seasonal analysis in Adamawa, northeast Nigeria.

LGA	Community	IWD C2 W	DT STR W	TZL COMP1	99-EVDT	Mean
Demsa	Mbula-kuli	4384	4220	3654	3518	**3944**
Demsa	Nassarawo-Demsa	4204	4127	3555	3353	**3810**
Girei	Daneyel	4131	3875	3532	3415	**3738**
Girei	Woroshi	4478	4283	3747	3651	**4040**
Gombi	Guyaku	4269	3956	3678	3687	**3898**
Gombi	Tawa	4505	4406	3769	3672	**4088**
Guyuk	Chikila	4351	4210	3599	3496	**3914**
Guyuk	Lakumna	3521	3474	2885	2563	**3111**
Hong	Dulmava	4501	4400	3762	3670	**4083**

Hong	Garari Hushere-Zum	4503	4313	3784	3717	**4079**
Numan	Bare	4328	4027	3647	3597	**3900**
Numan	Kikan_Kodomti	4275	4097	3622	3478	**3868**
Shelleng	Jonkolo-Lama	4179	3965	3471	3412	**3757**
Shelleng	Lakati-Libbo	4343	4060	3658	3592	**3913**
Song	Sabon-Gari	4018	3937	3336	3018	**3577**
Song	Suktu	4096	4000	3369	3076	**3635**
Yola north	Yelwa-Jambore	4138	3920	3446	3311	**3704**
Yola South	Fufure	4488	4387	3704	3299	**3970**
Mean		**4262**	**4092**	**3568**	**3418**	

3.3. Calibration, evaluation and application of the CROPGRO model in DSSAT to simulate performance of cowpea varieties in selected communities in Adamawa and Borno States

3.3.1. Methodology

3.3.1.1 Model calibration

Six experiments were conducted in two sites at Bayero University Kano and ABCOA, Danbatta both in the Sudan savannas of Nigeria from 2016 to 2018 cropping seasons. Each experiment consisted of three cowpea varieties (UAM091051-1, IT99K-573-1-1 and IT90K-277-2) of varying maturity group and yield potentials. The experiments were laid out in RCBD with three replications each. These experiments were conducted under optimum management practices. Soil samples were collected from the experimental sites and analyzed and results input in the model during model calibration. Parameters measured and optimized during the calibration process included days to 50% flowering, days to maturity and final grain yield (kg ha^{-1}) at harvest maturity. Calibration of a model is the adjustment of the model's parameters so that the output will be comparable to the data obtained from field experiments. We first calibrated soil parameters, then the genetic coefficient for the cowpea variety and finally, the experimental data. CROPGRO-Cowpea model requires 15 cultivar coefficients (CSDL, PPSEN, EM-FL, FL-SH, FL-SD, SD-PM, FL-LF, LFMAX, SLAVR, SIZLF, XFRT, WTPSD, SFDUR, SDPDV, and PODUR) that describe the growth and development characteristics for each individual cultivar The cultivar coefficients for the three cultivars UAM091051-1, IT99K-573-1-1 and IT90K-277-2 were generated from the existing cultivars in DSSAT. The existing cultivars with the same maturity group and characteristics of a tropical cowpea varieties were used to generate the coefficients. IT96D-748F was used for IT99K-573-1-1 while IT90K-277-2 already in the DSSAT was used as template for the IT90K-277-2 and UAM09 1051-1. The cultivar coefficients for each cultivar were determined through trial and error of the model and by comparing simulated and observed data, following the procedures described by *Hoogenboom et al.* (1999).

3.3.1.2. ***Model validation***

The performance of the model was validated with the four independent data sets collected from the population density trials for the three cowpea varieties using three levels (133,333, 266,666 and 400,000 Plants ha^{-1}). The experiments were conducted from 2016 to 2018 at Abuja and Zaria in the northern Guinea savanna zone. The treatment consisted of population density and cowpea varieties. A split-plot design with three replications was used. The main plot treatment consisted of three population density (133,333, 266,666 and 400,000 Plants ha^{-1}) levels and the subplot treatments was assigned to three cowpea (IT99K-573-1-1, IT90K-277-2 and UAM 09 1051-1) varieties.

Soil and weather data were collected from the experimental sites and used as inputs for model validation. For validation of the model, only grain yield outputs of the model were compared with observed grain yields obtained from the validation experiments. An analysis of the degree of coincidence between simulated and observed values was statistically determined with the following methods: (i) Root Mean Square Error (RMSE), this reflects the extent of the mean variance between simulated and observed data and it is a good measure of how accurately the model predicts the response. A good value of the RMSE should approach zero (Halder et al. 2017). (ii) Wilmott index of agreement (d-index) Willmott (1982), the nearer the value of d to 1, the better the prediction.

3.3.1.3. Model application (Seasonal analysis)

The model was applied to test the performance of different cowpea varieties in 18 and 15 communities in Adamawa and Borno States, respectively, using the seasonal analysis tool of DSSAT v4.7. The seasonal analysis was set to use July 20 as sowing date for all varieties at both States. A Single Super Phosphate (SSP) fertilizer was used in the model to supply 40 kg P_2O_5 at planting. The model was set to use 3 cm soil depth, with a recommended sowing density of 26.6 plants per square meter. The model was set to harvest when the crop reached harvest maturity. 30-year weather records (1985-2014) obtained from NIMET was used for seasonal analysis. Soil profile data for Adamawa and Borno were used for the scenario analysis. The mean grain yields for the 30 years for each variety and location were calculated using DSSAT.

3.3.2. Results

3.3.2.1 Model calibration

The results for the model calibration experiments for cowpea varieties are presented in Figures 5-7 A close agreement was obtained between simulated and observed values for all three measured parameters. The statistical values of simulated and measured days to anthesis and physiological maturity ranged between (RMSE = 0.82 to 2.37 days) and (d-index = 0.76 to 0.96) for all varieties. The comparison between simulated and observed grain yield were also quite good for all the cowpea varieties. The RMSE values for grain yield ranged between 123 kg ha^{-1} for UAM 09 1051-1 to 270 kg ha^{-1} for IT99K-573-1-1 while d-index value was 0.77, 0.81 and 0.89 for IT99K-573-1-1, IT90K-277-2 and UAM 09 1051-1, respectively.

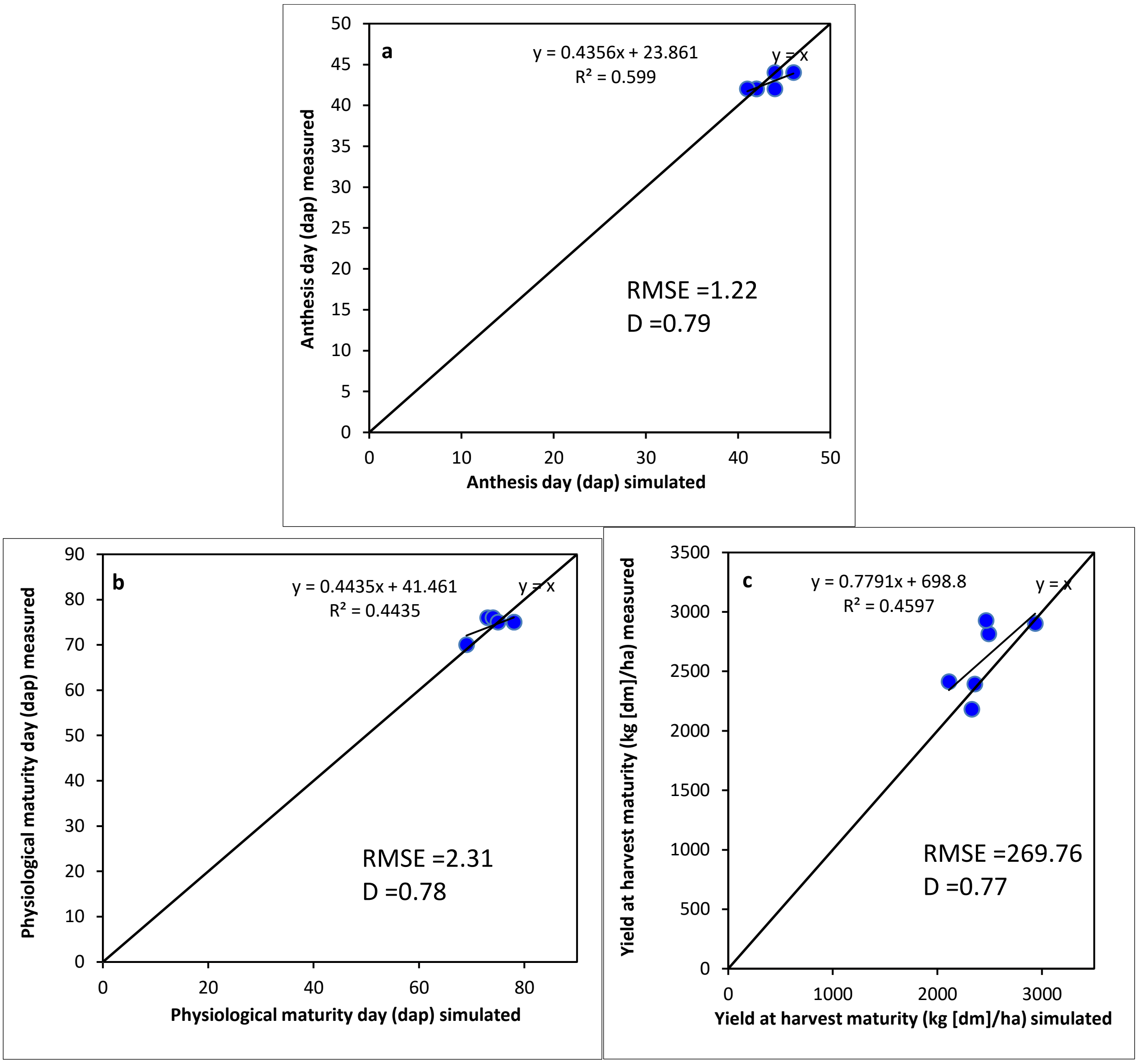


Fig. 3.5 Comparison of simulated and measured anthesis (a), physiological maturity (b) and grain yield at maturity (c) for IT99K-573-1-1 cowpea variety.

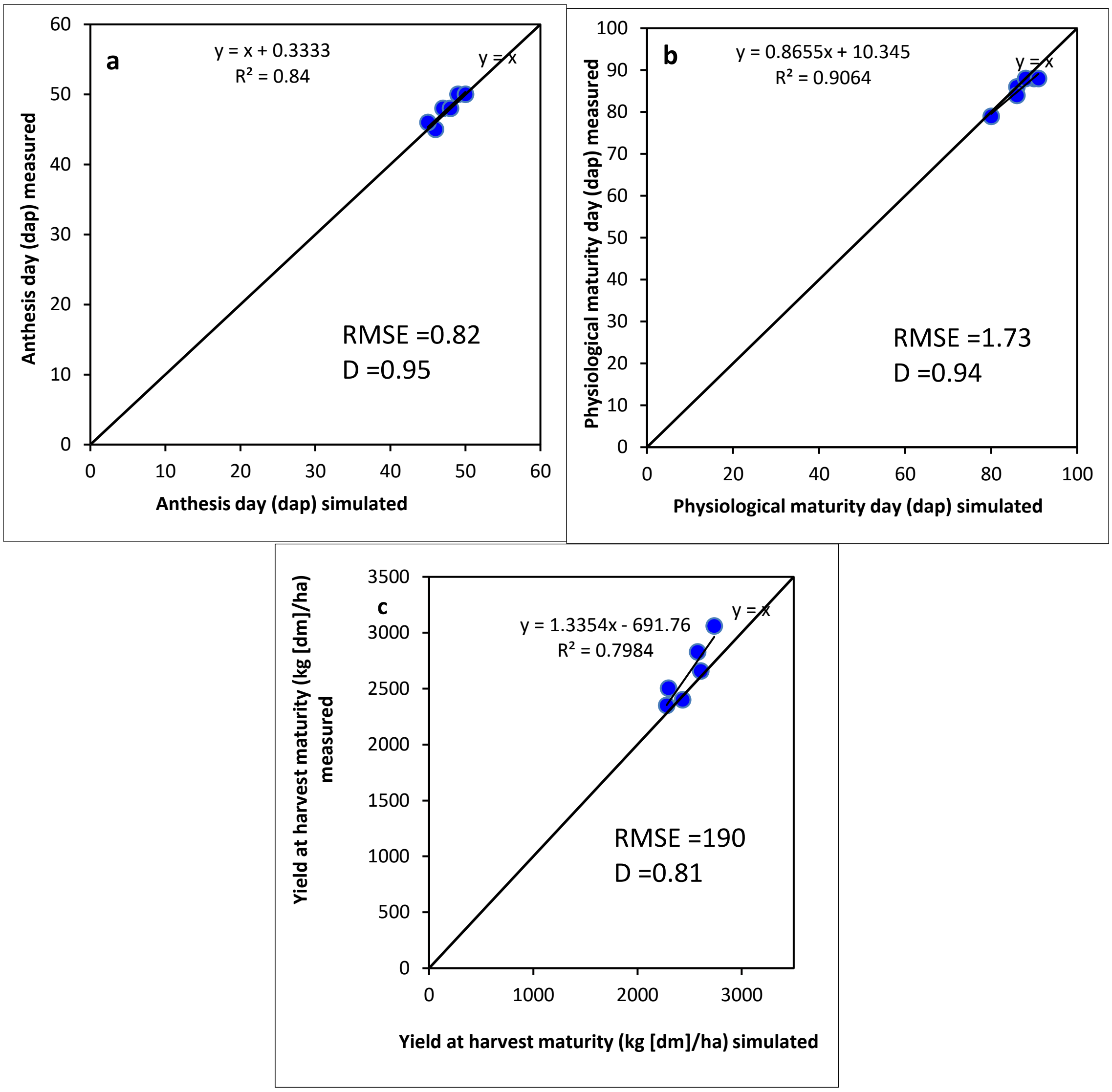
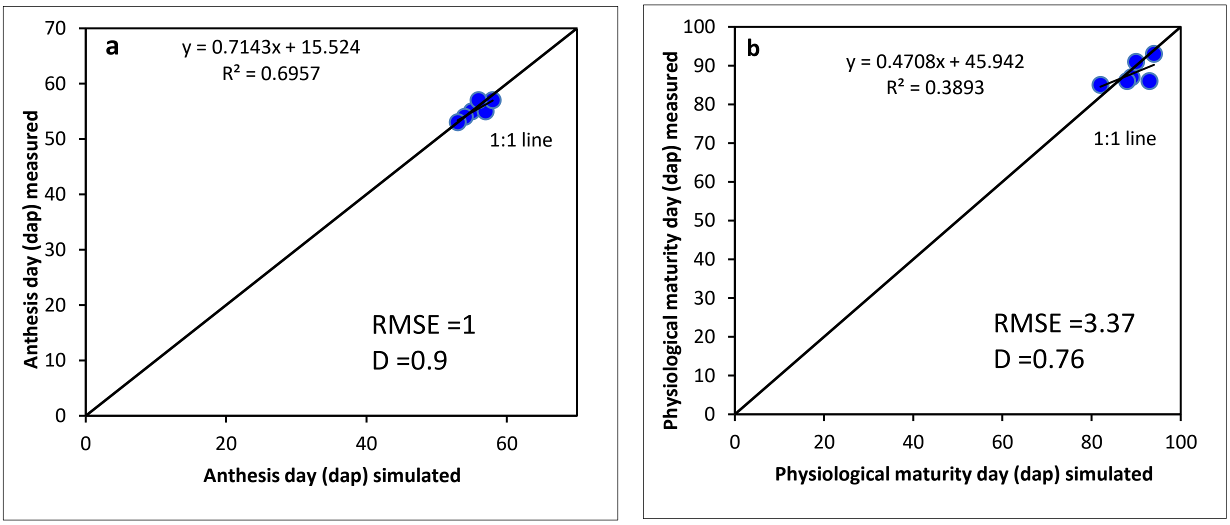


Fig. 3.6 Comparison of simulated and measured anthesis (a), physiological maturity (b) and grain yield at maturity (c) for IT90K-277-2 cowpea variety.



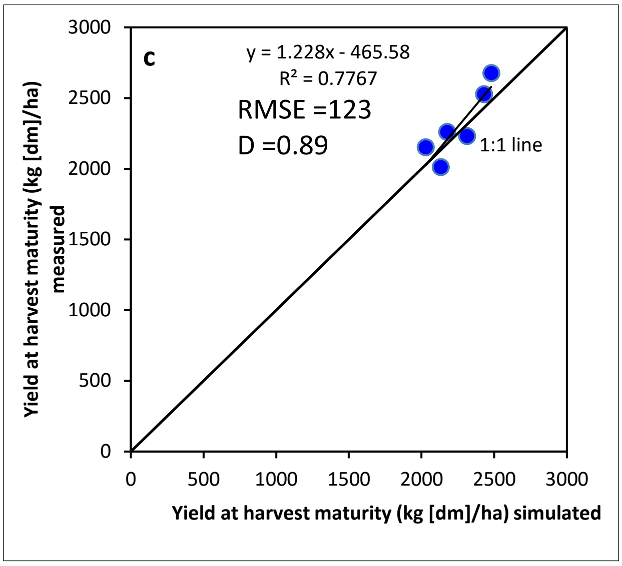


Fig. 3.7 Comparison of simulated and measured anthesis (a), physiological maturity (b) and grain yield at maturity (c) for UAM 09 1051-1 cowpea variety.

3.3.2. 2 Model validation

The accuracy of the CROPGRO model simulations and performance of genetic coefficients were assessed by running the model with independent data sets collected during 2016, 2017 and 2018 seasons for IT99K-573-1-1, IT90K-277-2 and UAM 09 1051-1using three population densities (133,333, 266,666 and 400,000) at Zaria. Grain yield at maturity was used for model evaluation (Table 7). The model's evaluation of grain yield was good at all population densities of the three varieties. In all the years, the model slightly underestimated or overestimated the measured parameters for all the three cowpea varieties at various population densities. However, the under or over estimations were within the acceptable range of below 25 %. There was a good fit in the model prediction of grain yield with low RMSE and high *d-index* values. The values of RMSE for the three varieties ranged from 118.1 to 176.3 kg ha^{-1}. In all cases, d-index values for grain yield were above 0.80 indicating that the model is robust and accurate in measuring grain yield.

Table 3.7 Simulated (S), observed (O) and simulated minus observed (S - O) of cowpea grain yield obtained from validation experiments conducted at Zaria over a three-year period.

Location	Year	Density	IT99K-573-1-1			IT90K-277-2			UAM 09 1051-1		
			S	O	S - O	S	O	S - O	S	O	S - O
Zaria	2016	133,333	1860	1818	42	1522	1376	146	1575	1337	238
		266,666	1864	1920	-56	1421	1413	8	1593	1363	230
		400000	1879	1899	-20	1433	1400	33	1672	1925	-253
Zaria	2017	133,333	1483	1602	-119	1936	1718	218	1969	2021	-52
		266,666	1504	1742	-238	2004	2185	-181	2080	2120	-40
		400000	1537	1712	-175	2102	2081	21	2167	2074	93
Zaria	2018	133,333	1918	1885	33	2314	2207	107	1575	1337	238
		266,666	1945	1878	67	2366	2400	-34	1593	1363	230
		400000	1602	1717	-115	2381	2296	85	1672	1925	-253
RMSE				*118.1*			*129.2*			*176.31*	
d value				*0.83*			*0.96*			*0.9*	

d, Willmott index of agreement (Willmott, 1982) ranging from 0 to 1, 1 being perfect agreement.

3.3.2.3 Model application (Seasonal analysis)

Results of seasonal analysis for mean grain yields in different locations conducted by the DSSAT model over 30-year period are presented in Tables 8 and 9 for Borno and Adamawa, respectively. In the two States, location had significant long-term effect on grain yield of all the varieties. On average, the varieties produced higher grain yield in Borno than in Borno with the medium maturing *Striga* resistant variety (IT99K-573-1-1) recording the highest grain yield of above 1-ton ha^{-1}. Average yield across locations, Mathau in Biu gave the highest grain yield of 1116 kg ha^{-1} and the lowest grain of 960 kg ha^{-1} was obtained at Bila Gusi in Kwayakusar in Borno State while Guyaku at Gombi in Adamawa, gave the highest grain yield of 1101 kg ha^{-1} and the lowest grain yield of 731 kg ha^{-1} was observed at Yola north.

Overall, the model simulated low yields for all cowpea varieties when compared with yields obtained under experimental conditions. We will continue to work with the developers of the model to refine it for better simulation of cowpea performance. Because of the low incidence of the parasitic weed *Striga gesneroides* in Adamawa State, all the three cowpea varieties can be recommended for production there. In Borno State where Striga is a problem, the two varieties (IT99K-573-1-1 and UAM 09 1051-1) which are completely resistant to *Striga* are recommended for dissemination.

Table 3.8 Cowpea grain yield (kg ha^{-1}) results of 30 years (1985-2014) seasonal analysis in Borno, northeast Nigeria.

LGA	**Community**	IT99K-573-1-1	IT90K-277-2	UAM 09 1051-1	Mean
Bayo	Balbaya	1102.5	1035.1	1010.5	**1049.4**
Bayo	Briyel	1113.6	1037.3	1020.8	**1057.2**
Bayo	Jara-Dali	1111.6	1036.6	1020.0	**1056.1**
Biu	Buratai	1076.8	1010.4	991.3	**1026.2**
Biu	Kabura	1108.6	1034.4	1037.2	**1060.1**
Biu	Tum	1088.4	1017.8	976.4	**1027.5**
Biu	Mathau	1115.9	1033.7	1040.3	**1063.3**
Hawul	Kwajaffa	1092.4	1038.0	1037.7	**1056.0**
Hawul	Puba Vidau	1088.3	1039.3	1038.4	**1055.3**
Hawul	Sakwa Hema	1092.4	1038.0	1037.7	**1056.0**
Kwayakusar	Bila Gusi	1004.8	962.3	960.2	**975.8**
Kwayakusar	Kurbo Gayi	1113.4	1037.7	1021.6	**1057.6**
Shani	Gwaskara	1108.1	1041.1	1044.2	**1064.5**
Shani	Kubo	1007.9	962.2	962.2	**977.4**
Shani	Lakundum	1107.5	1041	1044	**1064.2**
Mean		**1088.8**	**1024.3**	**1016.2**	

Table 3.9 Cowpea grain yield (kg ha^{-1}) results of 30 years (1985-2014) seasonal analysis in Adamawa, northeast Nigeria.

LGA	Community	IT99K-573-1-1	IT90K-277-2	UAM 09 1051-1	Mean
Demsa	Mbula Kuli	1060.4	970.7	964.8	**998.6**
Demsa	Nassarawo-Demsa	1022.7	973.3	961.9	**986.0**
Girei	Daneyel	996.8	947.4	940.6	**961.6**
Girie	Wuroshi	1009.5	938.1	933.2	**960.3**
Gombi	Tawa	1085.2	1001.7	984.8	**1023.9**
Gombi	Guyaku	1100.5	1067.3	1057.5	**1075.1**
Guyuk	Chikila	992.0	952.5	951.9	**965.5**
Guyuk	Lakumna	1010.5	961.3	962.0	**977.9**
Hong	Dulmava	1039.5	1003.1	1003.4	**1015.3**
Hong	Garari_Hushere Zum	1071.7	1000.2	983.9	**1018.6**
Numan	Bare	1063.3	948.6	936.8	**982.9**
Numan	Kikan_Kodomti	1012.8	968.8	956.0	**979.2**
Shelleng	Jonkolo – Lama	1011.3	958.9	955.1	**975.1**
Shelleng	Lakati_Libbo	1051.3	964.7	951.6	**989.2**
Song	Sabon Gari	1070.9	979.7	975.5	**1008.7**
Song	Suktu	1070.9	979.7	975.5	**1008.7**
Yola North	Yelwa -Jambore	731.1	753.3	771.3	**751.9**
Yola South	Fufore	1072.5	1018.7	1007.3	**1032.8**
Mean		**1026.3**	**966**	**959.6**	

3.4. Calibration, evaluation and application of the CROPGRO-Soybean model in DSSAT to simulate performance of soybean varieties in selected communities in Adamawa and Borno States

3.4.1. Methodology

3.4.1.1. Model calibration

For the calibration of the model for soybean, 8 experiments were conducted across two sites at Bayero University, Kano and ABCOA, Danbatta in the Sudan savannas of Nigeria. Prior to the establishment of the experiment, soil samples were collected from the sites and analysed for nutrient content. Each experiment consisted of five soybean (TGX1904-6F, TGX 1951-3F, TGX1835-10E, TGX1987-10F and TGX1448-2E) varieties that were established in a randomized complete block design (RCBD) and replicated three times from 2016 to 2019. The experiments were conducted under optimum management practices to avoid stresses from water, nutrients, pests and diseases. Parameters measured include days to 50% flowering, days to maturity, grain yield (kg ha^{-1}) and top weight (kg ha^{-1}).

The soybean model was calibrated by determining the cultivar coefficients for the five cultivars TGX1904-6F, TGX 1951-3F, TGX1835-10E, TGX1987-10F and TGX1448-2E. The CSM-CROPGRO-Soybean model requires 15 cultivar coefficients (CSDL, PPSEN, EM-FL, FL-SH, FL-SD, SD-PM, FL-LF, LFMAX, SLAVR, SIZLF, XFRT, WTPSD, SFDUR, SDPDV, and PODUR) that describe the growth and development characteristics for each individual cultivar. As these were not available for the cultivars used in these experiments, the existing cultivar coefficients for the maturity group (MG) 7 were used for the cultivar TGX 1835-10E; while the existing cultivar Jupiter 10 was used as a template for the other cultivars at the start of the calibration because they represent the characteristics of a tropical soybean varieties. The cultivar coefficients for each cultivar were determined through trial and error of the model and by comparing simulated and observed data, following the procedures described by Hoogenboom et al. (1999). In the CROPGRO-Soybean model, the GSPs were calibrated by comparing simulated and measured data for days to anthesis, days to maturity, grain yield and top weight from the calibration experiments.

3.4.1.2. Model validation

The performance of the model was validated with the four independent data sets collected from the P response trials for the five soybean (TGX1835-10E, TGX 1904-6F, TGX1951-3F, TGX1987-10F and TGX1448-2E) varieties using three P levels (0, 20 and 40 Kg P ha^{-1}). The soybean validation experiments were conducted at Doguwa and Zaria in the northern Guinea savanna zone. A split-plot design with three replications was used for each experimental field. The main plot treatments consisted of three phosphorus fertilizer rates and the subplot treatments were five soybean varieties. Soil and weather data were collected for use as input during model validation. Data collected included days to flowering and maturity, final grain yield, biomass yield, and harvest index. For the validation, only final grain yield outputs of the model were compared with observed values. To evaluate model performance and accuracy in prediction, statistical indicators of root mean square error (RMSE) and the Willmott (1982) index of agreement (d value) were computed from observed and simulated variables. The values of RMSE and d-value indicate the degree of agreement between the predicted values with their corresponding observed values. A low RMSE value is desirable. The d value is a better indicator of model performance, particularly relative to 1:1 line, and values closer to 1 indicate better prediction while a d value of zero indicates no predictability. The model statistics used to evaluate model performance were based on previous model evaluation studies as indicated in the CERES-maize model.

3.4.1.2. *Model application*

Sensitivity analysis was carried out to test the performance of soybean grain yield in diverse locations; 18 locations in Adamawa and 15 locations in Borno using the seasonal analysis tool of DSSAT v4.7. The planting date was set to 22nd June for Adamawa and 20th June for Borno. Phosphorus fertilizer was set to supply 40 kg P ha^{-1}. Generally, sowing was done at soil depth of 5 cm, with a sowing density of 53.3 plants m^{-2}. The model was set to harvest when the crop reached harvest maturity. 30-year weather records (1985-2014) were obtained for each location from NIMET and used for seasonal analysis. Soil data from Adamawa and Borno was used for the scenario analysis. The mean yields for 30 years for each variety and location were calculated using DSSAT model application.

3.4.2. Results

3.4.2.1. *Model calibration*

Except for tops weight at maturity, the CROPGRO-Soybean model adequately simulated days to flowering, days to physiological maturity and grain yield of the five varieties using the calculated coefficients (Figures 8-12). Observed and simulated values were in good agreement for days to flowering, days to physiological maturity and grain yield of the five soybean varieties. The d-index values ranged from 0.80 to 0.91 for flowering, 0.88 to 0.92 for maturity and 0.74 to 0.94 for grain yield. Better fits were observed with d-index of agreement of 0.74 and above for all the varieties. The statistical evaluation of the agreements between observed and simulated values using RMSE values indicated good agreements for all the soybean varieties, for days to flowering with the RMSE ranging between 0.61 and 1.38 days, RMSE for days to physiological maturity ranging from 1.2 to 2.2 days while for grain yield the RMSE values ranged between 106 and 219 kg ha^{-1}.

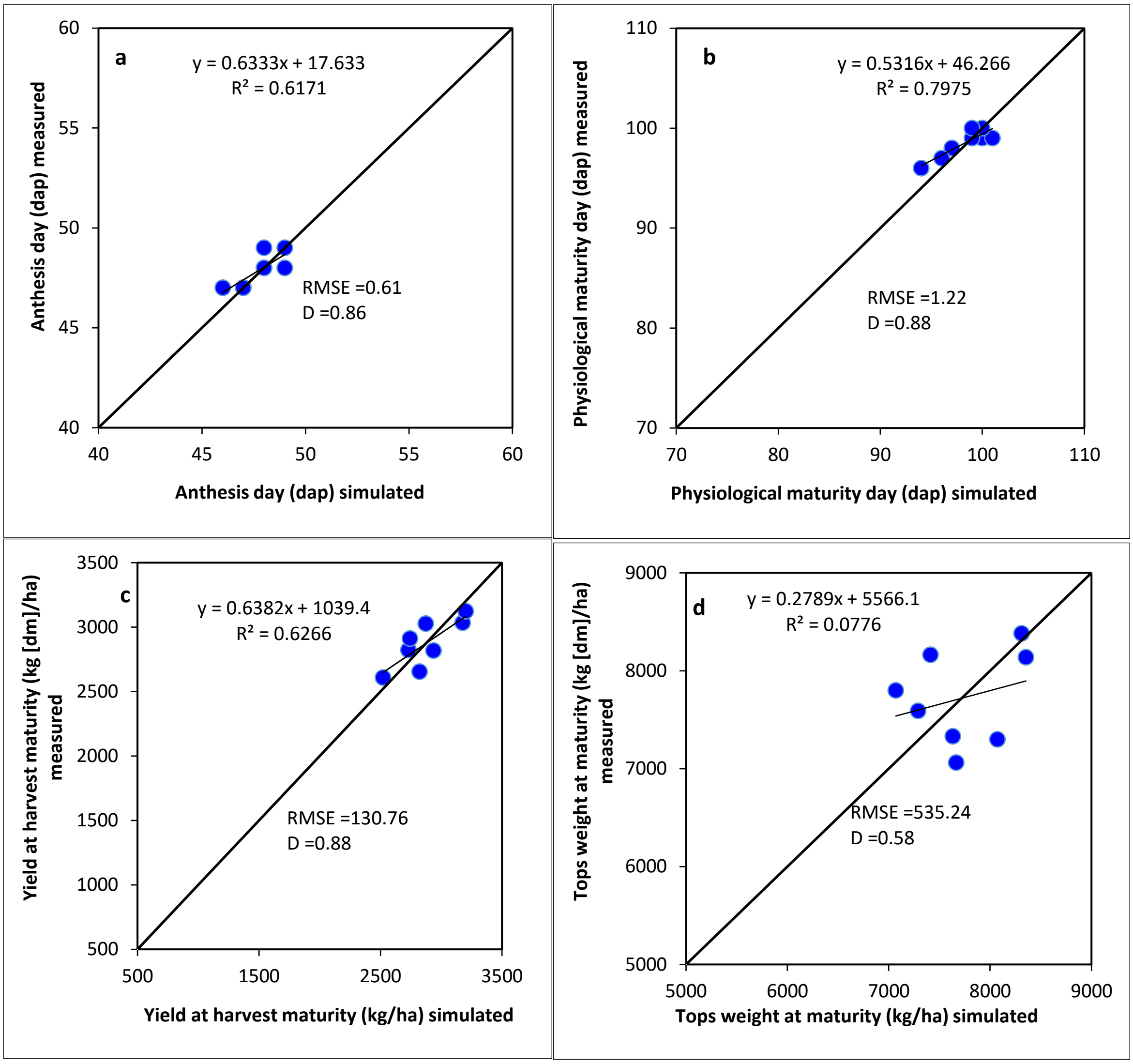


Fig. 3.8 Comparison of measured and simulated days to flowering (a), days to physiological maturity (b), grain yield (c) and dry matter (d) for the calibration of TGX1835-10E in Danbatta and BUK - Kano.

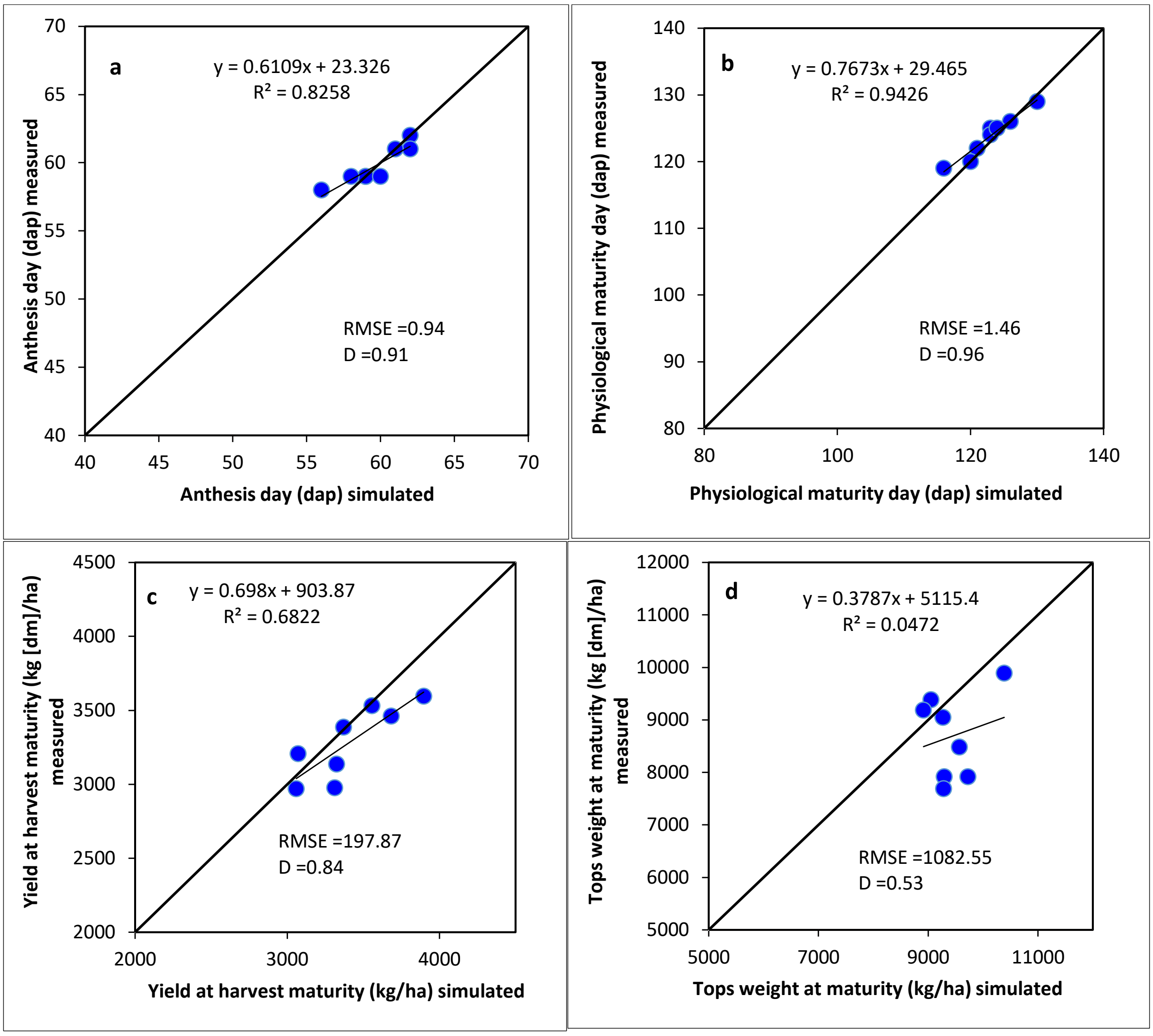


Fig. 3.9 Comparison of measured and simulated days to flowering (a), days to physiological maturity (b), grain yield (c) and dry matter (d) for the calibration of TGX1904-6F in Danbatta and BUK - Kano.

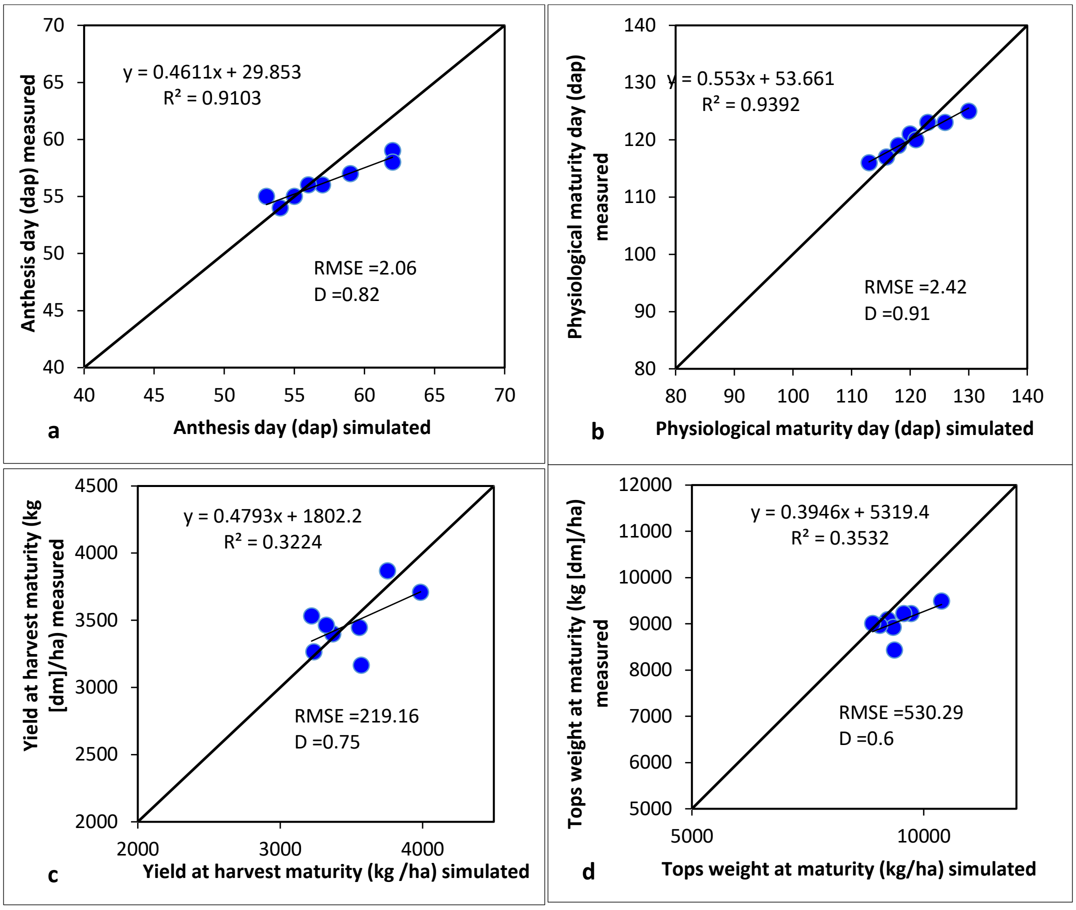


Fig. 3.10 Comparison of measured and simulated days to flowering (a), days to physiological maturity (b), grain yield (c) and dry matter (d) for the calibration of TGX1951-3F in Danbatta and BUK - Kano.

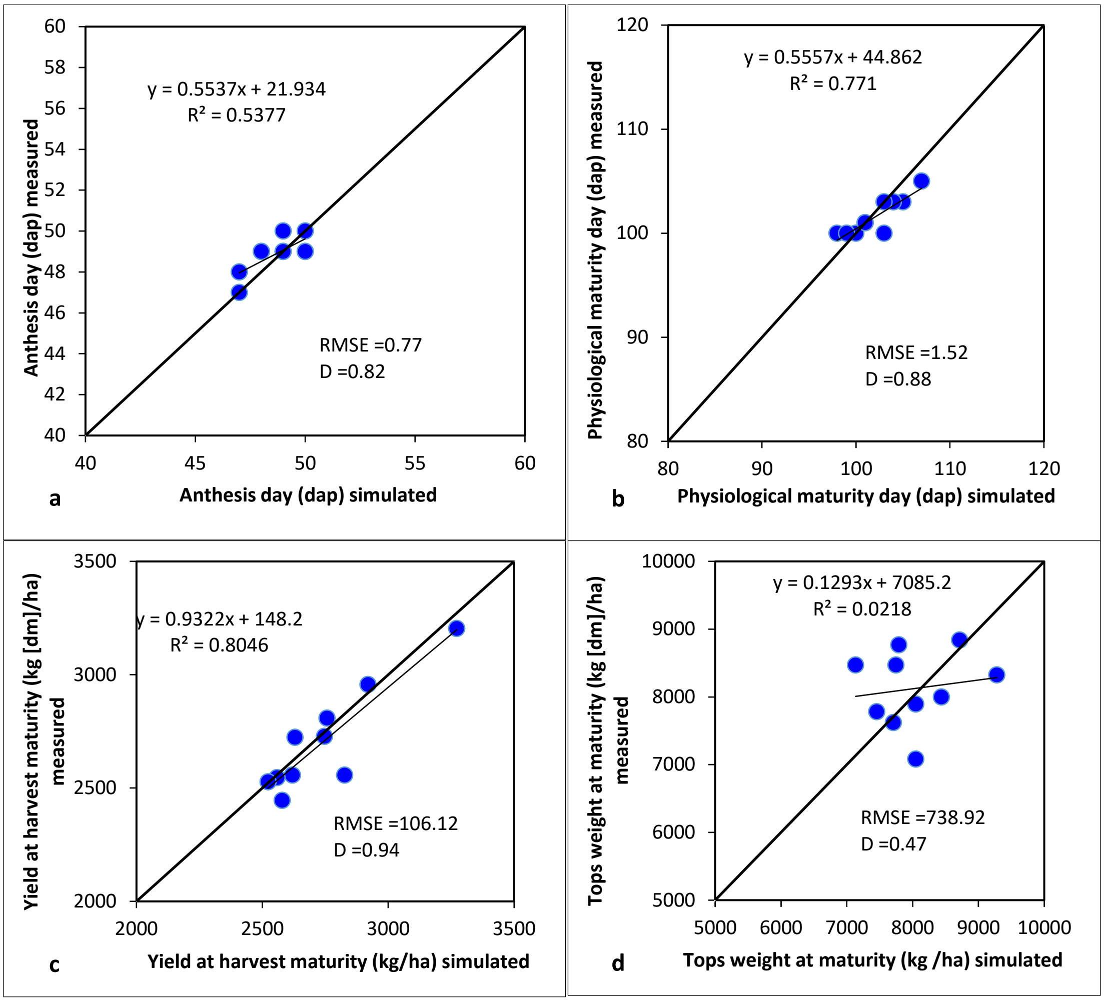


Fig. 3.11 Comparison of measured and simulated days to flowering (a), days to physiological maturity (b), grain yield (c) and dry matter (d) for the calibration of TGX1987-10F in Danbatta and BUK - Kano.

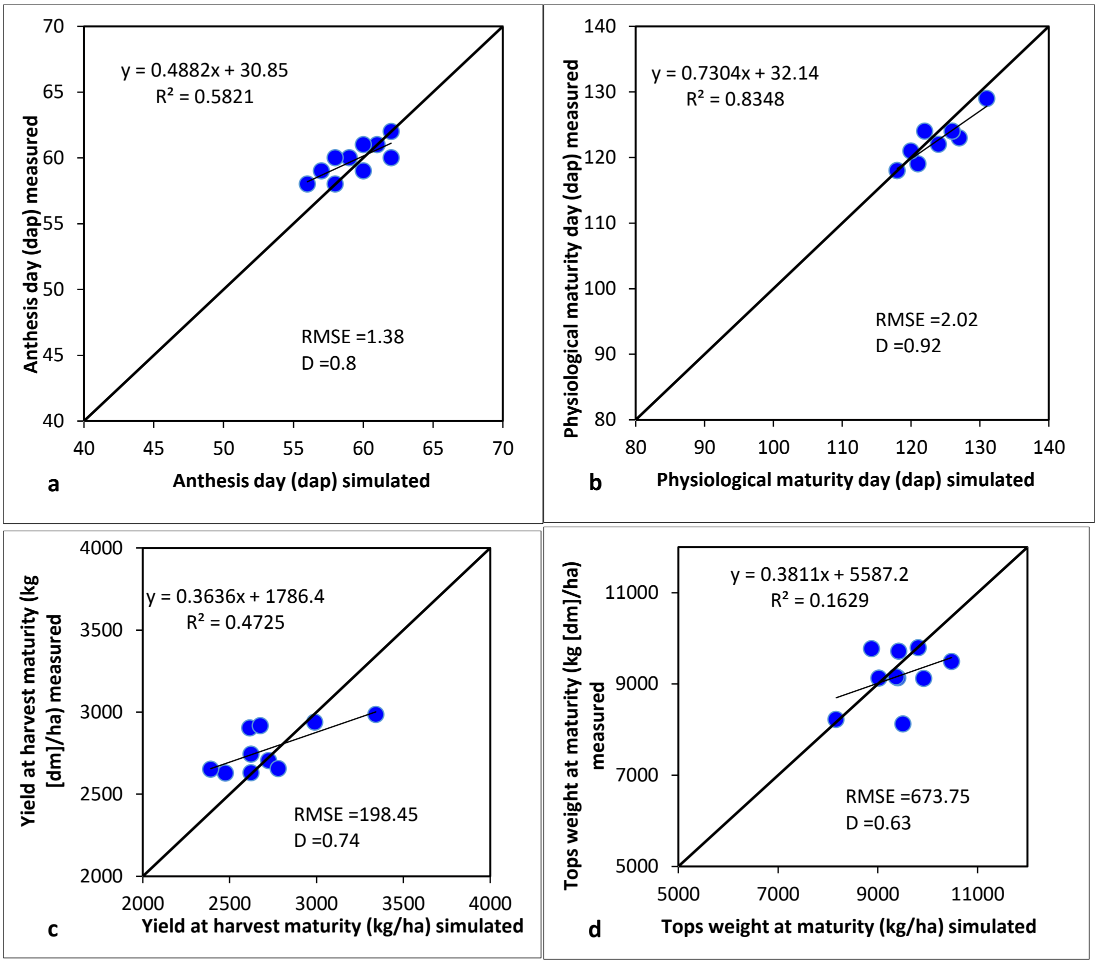


Fig. 3.12 Comparison of measured and simulated days to flowering (a), days to physiological maturity (b), grain yield (c) and dry matter (d) for the calibration of TGX1448-2E in Danbatta and BUK - Kano.

3.4.2.2. Model evaluation/validation

The accuracy of the CROPGRO-Soybean model simulations and performance of genetic coefficients were assessed by running the model with independent data sets collected from 2016 to 2019 cropping seasons for TGX1835-10E, TGX1904-6F, TGX1951-3F, TGX1987-10F and TGX1448-2E using three levels of phosphorus (0, 20 and 40 kg P ha^{-1}) application at Doguwa and Zaria. Grain yield at maturity was used for model evaluation (Tables 10 and 11). The model's evaluation of grain yield was good at all P levels for the five varieties in each location. In all the locations and years, the model slightly over predicted or under predicted grain yield for all the five soybean varieties at various P levels. However, the over or under predictions were within the acceptable range of below 25 %. In all the locations there was a good fit in the model prediction of grain yield with low RMSE and high *d-index* values. The values of RMSE for the five soybean varieties ranged from 83.3 to 280 kg ha^{-1}. In all cases, d-index values for grain yield were above 0.93 indicating that the model is robust and accurate in measuring grain yield. These results showed that the model was able to reasonably simulate grain yield of soybean for different fertilizer rate with low RMSE and high R^2 > 0.7. Even though there are difference in soil and weather conditions among the environments, good agreements were recorded between observed and simulated variables indicating that the cultivar coefficients derived were accurately calibrated. This suggests that the DSSAT CROPGRO-soybean model is sensitive to management and environmental variables such as nutrient supply. This result confirms the ability of the CROPGRO-Soybean model to accurately predict growth and yield of rainfed soybean under different management practices. In general, the statistical indices were all within the acceptable ranges for model evaluation indicating that DSSAT-CROPGRO model could be used as a tool for decision making in the Nigeria Savannas.

Table 3.10 Simulated (S), observed (O) and simulated minus observed (S - O) grain yield of TGX1835-10E, 1904-6F and TGX1951-3F obtained from validation experiments conducted at two locations over a four-year period**.**

Location	Year	P_2O_5	TGX1835-10E			TGX1904-6F			TGX1951-3F		
			S	**O**	**S - O**	**S**	**O**	**S – O**	**S**	**O**	**S - O**
Doguwa	2016	0	374	224	150	449	535	-86	479	528	-49
		20	1517	1435	82	1542	1620	-78	1391	1379	12
		40	1781	1713	68	2014	1989	25	2106	2089	17
Zaria	2016	0	129	125	4	162	100	62	168	47	121
		20	1391	1226	165	1575	1684	-109	1074	1009	65
		40	1652	1659	-7	1905	1908	-3	1980	1950	30
	2017	0	111	82	29	144	85	59	165	93	72
		20	1142	1135	7	1027	1252	-225	1155	1273	-118
		40	1325	1439	-114	1164	2049	-885	1381	1914	-533
	2018	0	256	120	136	172	50	122	180	52	128
		20	1330	1120	210	1146	1096	50	1057	1096	-39
		40	1227	1132	95	1400	1307	93	1602	1710	-108
	2019	0	122	183	-61	162	176	-14	170	159	11
		20	1408	1605	-197	1545	1468	77	1601	1856	-255
		40	1861	1862	-1	1914	1706	208	2015	2391	-376
RMSE					*111*			*280*			*194*
d value					*0.99*			*0.96*			*0.98*

Table 3.11 Simulated (S), observed (O) and simulated minus observed (S - O) grain yield of TGX1987-10F and TGX1448-2E obtained from validation experiments conducted at two locations over a four-year period

Location	Year	P_2O_5	TGX1987-10F			TGX1448-2E		
			S	**O**	**S - O**	**S**	**O**	**S - O**
Doguwa	2016	0	400	489	-89	410	567	-157
		20	1586	1644	-58	1399	1354	45
		40	1963	1923	40	1553	1485	68
Zaria	2016	0	125	124	1	162	80	82
		20	1620	1675	-55	1190	1195	-5
		40	1836	1834	2	1631	1665	-34
	2017	0	107	66	41	141	48	93
		20	1129	973	156	929	872	57
		40	1289	1075	214	1036	1016	20
	2018	0	137	120	17	163	52	111
		20	1350	1331	19	1075	988	87
		40	1675	1539	136	1329	1232	97
	2019	0	125	426	-301	163	128	35
		20	1524	1596	-72	1075	989	86
		40	1949	1928	21	1329	1208	121
RMSE					116.36			83.29
d-value					0.99			0.99

d, Willmott index of agreement (Willmott, 1982) ranging from 0 to 1, 1 being perfect agreement.

3.4.2.3. Model application (Seasonal analysis)

The mean simulated grain yields from 30 years' seasonal analysis for five soybean varieties are presented in Tables 12 and 13. In Borno, the highest grain yield was produced by the variety TGX1951-3F and the lowest grain yield was produced by TGX1448-2E. The same trend was observed in Adamawa. In Borno, , Puba Vidau in Hawul gave the highest grain yield of 1843 kg ha^{-1} and the lowest grain of 1353 Kg ha^{-1} was simulated at Bila Gusi in Kwayakusar. In Adamawa, Chikila in Guyuk gave the highest grain yield (1772 kg ha^{-1}) while Mbula Kuli in Demsa gave the lowest grain yield (588 kg ha^{-1}). In Both Adamawa and Borno, TGX1951-3F produced grain yields that were 20 and 21% higher than that of TGX1448-2E, 23 and 17% higher than that of TGX1835-10E, 17 and 13% higher than that of TGX1987-10F and 8 and 9 % higher than that of TGX1904-3F, respectively. TGX1904-6F produced grain yields that was 11% higher than that of TGX1448-10F and 14% higher than that of TGX1835-10E in Adamawa and Borno, respectively, while TGX1987-10F was 8% higher than TGX1448-2E in Borno only. TGX 1987-10F, TGX1835-10E and TGX1448-2E did not show much difference on grain yield in all the study areas. Though the variety, TGX1448-2E has been widely promoted in Nigeria and is a ruling variety, the two varieties TGX1951-3F and TGX1904-6F have more promise in terms of yield and are therefore recommended for dissemination in the two States.

Table 3.12 Soybean Grain yield (kg ha^{-1}) results of 30 years (1985-2015) seasonal analysis in Borno, northeast Nigeria.

LGA	**Community**	**TGX1835-10E**	**TGX1904-6F**	**TGX1951-3F**	**TGX1987-10F**	**TGX1448-2E**	**Mean**
Bayo	Balbaya	1323	1353	1478	1365	1256	**1355**
Bayo	Briyel	1654	1680	1833	1714	1522	**1681**
Bayo	Jara-Dali	1545	1614	1751	1602	1479	**1598**
Biu	Buratai	1443	1457	1596	1494	1282	**1454**
Biu	Tum	1408	1407	1559	1460	1236	**1414**
Biu	Kabura	1651	1795	2003	1708	1548	**1741**
Biu	Mathau	1676	1682	1848	1721	1511	**1688**
Hawul	Kwajaffa	1702	1744	1942	1774	1528	**1738**
Hawul	Lakundum	1542	1777	1922	1607	1609	**1691**
Hawul	Puba Vidau	1676	1922	2096	1745	1776	**1843**
Hawul	Sakwa Sema	1345	1416	1568	1401	1304	**1407**
Kwayakusar	Bila Gusi	1281	1375	1495	1346	1269	**1353**
Kwayakusar	Kurbo Gayi	1620	1768	1907	1687	1601	**1717**
Shani	Gwaskara	1487	1664	1818	1536	1530	**1607**
Shani	Kubo	1430	1701	1817	1517	1510	**1595**
Mean		**1519**	**1624**	**1776**	**1578**	**1464**	

Table 3.13 Soybean Grain yield (kg ha^{-1}) results of 30 years (1985-2015) seasonal analysis in Adamawa, northeast Nigeria.

LGA	Community	TGX1835-10E	TGX1904-6F	TGX1951-3F	TGX1987-10F	TGX1448-2E	Mean
Demsa	Mbula Kuli	642	550	597	657	496	**588**
Demsa	Nassarawo-Demsa	1423	1752	1875	1510	1581	**1628**
Girei	Daneyel	1058	1117	1226	1107	1052	**1112**
Girie	Wuroshi	1457	1581	1733	1568	1302	**1528**
Gombi	Guyaku	976	953	1045	1009	889	**974**
Gombi	Tawa	1414	1665	1796	1474	1501	**1570**
Guyuk	Chikila	1477	1956	2108	1631	1686	**1772**
Guyuk	Lakumna	1429	1969	2081	1565	1689	**1747**
Hong	Dulmava	997	1249	1340	1049	1184	**1164**
Hong	Hushere Zum	1128	1247	1338	1163	1177	**1211**
Numan	Bare	1264	1257	1364	1306	1172	**1273**
Numan	Kodomti	1305	1449	1559	1366	1352	**1406**
Shelleng	Jonkolo - Lama	1220	1345	1455	1275	1258	**1311**
Shelleng	Lakati_Libbo	1251	1300	1414	1302	1201	**1294**
Song	Sabon Gari	1331	1595	1704	1391	1456	**1495**
Song	Suktu	973	1171	1275	1027	1079	**1105**
Yola North	Yelwa -Jambore	1019	1132	1240	1062	917	**1074**
Yola South	Fufure	1221	1216	1345	1276	1124	**1236**
Mean		**1199**	**1361**	**1472**	**1263**	**1229**	

3.5. Conclusions

Our Results show that CERES and CROPGRO models can accurately predict the performance of grain crop varieties in northern Nigeria. The soil and weather conditions in Adamawa and Borno State are variable. The models simulated higher grain yields of all the crops in Borno than in Adamawa. This may be due to better soil fertility conditions in Borno. Adamawa State lie mostly in the Guinea savannas which usually record higher rainfall than the Sudan savannas of Borno. In both States, the maize varieties IWD C2 W and DT STR W are recommended for production and dissemination. However, the yield produced by 99 EVDT is within the acceptable range for early maturing maize varieties in northern Nigeria and should be promoted alongside the medium-maturing varieties because of the uncertainty in the rainfall pattern. The model consistently simulated higher yields for two soybean varieties than those of the other varieties in all the sites in the two States. These varieties (TGX1951-3F and TGX1904-6F) are therefore recommended for dissemination in the two States. Because of the problem of the parasitic weed *Striga gesneroides* in Borno State, only two Striga-resistant varieties (IT99K-573-1-1 and UAM 09 1051-1) are recommended for dissemination. In Adamawa, where *Striga gesneroides* is not much of a problem, all the three varieties evaluated can be disseminated.

References

Adnan A.A., Diels J., Jibrin J.M., Kamara A.Y., Shaibu, A.S., Craufurd P., and Abebe Menkir (2020). CERES-Maize model for simulating genotype-by-environment interaction of maize and its stability in the dry and wet savannas of Nigeria. Field Crops Research, 253 (15) 107826. doi.org/10.1016/j.fcr.2020.107826

Badu-Apraku, B., Yallou, C.G., Alidu, H., Talabi, A.O., Akaogu, I.C., Annor, B., and Adoti, A. (2016). Genetic improvement of extra-early maize cultivars for grain yield and Striga resistance during three breeding ears. *Crop Science*, 56:2564–2578.

Badu-Apraku, B., Yallou, C.G., and Oyekunle, M. (2013). Genetic gains from selection for high grain yield and Striga resistance in early maturing maize cultivars of three breeding periods under Striga-infested and Striga-free environments. *Field Crops Research*, 147:54–67.

Banterng P., Hoogenboom, G., Patanothai, A., Singh, P., Wani, S.P., Pathak, P., Tongpoonpol, S., Atichart, S., Srihaban, P., Buranaviriyakul, S., Jintrawet, A., and Nguyen, T.C. (2010). Application of the Cropping System Model (CSM)-CROPGRO-Soybean for Determining Optimum management Strategies for Soybean in Tropical Environments. *Journal of Agronomy and Crop Science* (2010)

FAOSTAT (2018). Food and Agricultural Organization of the United Nations (FAO), FAO Statistical Database, from http://faostat.fao.org.

Halder, D., R.K. Pandab, R.K. Srivastavac, S. Kheroard (2017). Evaluation of the CROPGRO-Peanut model in simulating appropriate sowing date and phosphorus fertilizer application rate for peanut in a subtropical region of eastern India. *The Crop Journal*, 5 (4), 317-325.

He, J., J.W. Jones, W.D. Graham, and M.D. Dukes (2010). Influence of likelihood function choice for estimating crop model parameters using the generalized likelihood uncertainty estimation method. *Agricultural Systems,* 103:256–264. doi:10.1016/j.agsy.2010.01.006

Hoogenboom, G., Porter, C.H., Shelia, V., Boote, K.J. Singh, U., White, J.W., … Jones, J.W. (2017). Decision Support System for Agrotechnology Transfer (DSSAT) Version 4.7 (https://DSSAT.net). *DSSAT Foundation*, Gainesville, Florida, USA.

Jibrin, M.J., Kamara, A.Y., and Ekeleme, F. (2012). Simulating planting date and cultivar effects on dryland maize production using CERES-maize model. *African Journal of Agricultural Research* vol 7(40) pp. 5530-5536.

Kamara, A. (2017). Good agricultural practices for maize cultivation: The case study of West Africa Alpha Kamara, International Institute of Tropical Agriculture, Nigeria. In: Achieving sustainable cultivation of maize, Volume 2: Cultivation techniques, pest and disease control. Dr. David Watson Ed, CGIAR MAIZE Research Program, CIMMYT, Mexico. pp 49-60. Burleigh Dodds Science Publishing Ltd., Cambridge, UK.

Kamara, A.Y., A.Menkir, M.A.B. Fakorede, S.O. Ajala, B. Badu-Apraku, and I. Kureh. (2004). Agronomic performance of maize cultivars representing three decades of breeding in the Guinea savannas of West and Central Africa. J. Agric. Sci. 142:567–575.

Menkir, A. 2006. Assessment of reactions of diverse maize inbred lines to *Striga hermonthica* (Del.) Benth. *Plant Breeding*, 125:131–139.

Menkir, A., Badu-Apraku, B., Yallou, C.G., Kamara, A.Y., and Ejeta, G. 2007. Breeding maize for broad-based resistance to *Striga hermonthica. In:* Ejeta, G., *and* Gressel, J., *editors.* Integrating new technologies for Striga control: Towards ending the witch-hunt. *World Science Publication Co.,* Singapore. *p.* 99–114.

Omoigui, Lucky O. Catherine C. Danmaigona, Alpha Y. Kamara, Ebenezer J. Ekefan, and Michael P. Timko (2018). Genetic analysis of Fusarium wilt resistance in cowpea (V*igna unguiculata* Walp.). *Plant Breeding*, 137 (5) p. 773-781 https://doi.org/10.1111/pbr.12628

Ritchie, J.T., Singh, U., Godwin, D.C., and Bowen, W.T. 1998. Cereal growth, development, and yield. In: Tsuji, G. Y. et al. (eds.). Understanding options for agricultural production. Kluwer Academic Publishers, Dordrecht, The Netherlands. p. 79-98.

Tofa, A.I., Chiezey, U.F., Babaji, B.A., Kamara, A.Y., Adnan, A.A., Beah, A., and Adam, A.M. (2020). Modeling Planting-Date Effects on Intermediate-Maturing Maize in Contrasting Environments in the Nigerian Savanna: An Application of DSSAT Model. *Agronomy, 10*, 871. Doi:10.3390/agronomy10060871

UNDESA/PD (2015). *United Nations Department of Economic and Social Affairs, Population Division*. *World Population Prospects*: The 2015 Revision, Key Findings and Advance Tables. Working Paper No. ESA/P/WP.241.

Willmott, C.J. (1982). Some comments on the evaluation of model performance. Bull. Am. *Meteorological Society*, 63, 1309–1313.

Chapter 4

Simulating the performance of sorghum, pearl millet and groundnut cultivars in diverse agroecologies of North-Eastern, Nigeria: Application of APSIM models

Abstract

Rising population growth of 2.58% per annum in Nigeria will further increase the demand for agricultural products and increase pressure on farming systems, while negative environmental impacts must be minimized. However, producing enough food to eradicate extreme poverty and hunger that would meet our growing population, therefore, should go together with sustainable management of environmental resources (soil and water), and their various systems. The calibrated crop cultivars implemented in the Agricultural Production Systems sIMulator model (APSIM) were used to simulate the impacts of planting windows and crop varieties options adapted for sorghum, pearl millet, and groundnut in 33 sites comprised Adamawa and Borno States. The model predicted optimal PW suggests that any dates thereafter yield declines significantly. For sorghum production, higher mean grain yield (GY) was simulated for the early and medium-maturing sorghum cultivars than that of the late-maturing cultivars. The model simulated predicted about 50 days of PWs (29 May to 17 July) with optimal PWs varied from 30 May to 13 June for ICSV400, Samsorg-49, and Samsorg-45 respectively. The model predicted approximately 40 days of PWs (29 May to July 07) for CSR 01. For Samsorg-47 and SK5912 models predicted 32 days of PWs (May 29 to 29 June). Thus, early and medium maturing cultivars such as ICSV400, Improved Deko, CSR01 and Samsorg44 respectively for dissemination for most sites in Adamawa and Borno States. The late-maturing cultivar such as SK5912 should not be disseminated in most sites/LGAs while sites with simulated grain yield ≥ 2000 kgha^{-1} should adopt only early planting (PW1&PW2) for better productivity in both State. For Pearl millet, the simulated outputs of the three cultivars (Jirani, Sosat C88 and SuperSosat) estimated a low coefficient of variation (CV) ranging from 3 to 4 % for grain yield (GY), suggested high adaptability with low inter-annual variability of GY across the sites. This implies all the cultivars are suitable for cultivation with varying yield potential and thus recommend for dissemination across sites. Based on the simulated outputs, all the four (4) groundnut cultivars are adapted to the region and therefore, recommend for dissemination in both States except for sites/LGAs where the simulated with grain yield fall >1000 kgha^{-1} in Adamawa State and Borno State. However, farmers should be guided to adopt early planting window, alongside with developed good agronomic practices for higher productivity.

4.1. Introduction

Sorghum *(Sorghum bicolor* L. moench*)* is regarded as a major cereal for food grain and fodder, grown predominantly rainfed conditions in both semi-arid and sub-humid West Africa (Mishra et al., 2008; Akinseye et al., 2017) where it has a comparative advantage over other rainfed crops like maize and rice (Ajeigbe et al., 2018a, 2018b). Nigeria is the largest sorghum producing country in West and Central Africa region, accounting for about 23% of the sorghum production in Africa in 2016 (FMARD, 2011; FAOSTAT, 2018). The country produced 8.5 million tons in 2008, 9.3 million tons in 2009, and 10.0 million tons in 2010 with a projection of being the largest sorghum grain producer in the world by 2020. Sorghum was cultivated on about 10.845 million hectares in 2014, representing about 50% of the total area under cereal crop production and about 13% of the total arable land in the country. The growth and yield of sorghum can be limited by both abiotic and biotic factors, including weather (rainfall and temperature), soil conditions (water, and nutrients), parasitic weeds (Striga), disease incidence and management practices (cultivar, fertilization) (Ajeigbe et al., 2010b).

Pearl millet *(Pennisetum glaucum* (L.) R. Br.) The annual pearl millet production in Nigeria between 2014 and 2016 ranged from 1.15 to 1.55 million tons, representing about 5% of total world production with the average yield of 903 kg ha^{-1}, which ranked Nigeria as the third world's largest producer after Niger and India (FAOSTAT, 2018). In Nigeria, pearl millet is grown primarily for grain used for human consumption. The Stover is also of great economic importance for livestock feed, building materials and fuel. Pearl millet is drought-tolerant and early maturing with high water use efficiency. Pearl millet provides grain for human consumption and Stover for livestock in the Arid and Semi-Arid Tropics (Ajeigbe *et al.*, 2019). It has high nutritional value and exceptional tolerance to drought and high temperature. Under semi-arid conditions, rainfall and soil fertility dictate crop performance and cropping patterns (Mweu *et al*. 2016). Pearl millet flourishes satisfactorily and can be cultivated under low rainfall (200 - 250 mm), which makes it one of the hardy cereal crops in the Arid and Semi-Arid Tropics. These make pearl millet the most suitable crop in the Sahel region of West Africa including Nigeria. Although average pearl millet yields in Nigeria are, lower than for other cereal crops, improved agronomic practices and varieties have been found to lead to more efficient use of photosynthetically active radiation (PAR), water, and nutrients, especially N, resulting in a significant increase in grain and Stover yields.

Groundnut *(Arachis hypogaea* L.*)* is the fourth most important oil seed crop in the world (Mukhtar, 2009). The groundnut production globally estimated at 37.1 million metric tons grown on 26.4 million hectares, with an average productivity of 1.4 tons/ha (FAO, 2017). The production of the crop is concentrated in Asia and Africa, where it is grown mostly under rain-fed conditions with limited external inputs. Developing countries constitute 97% of the global area cultivated. Groundnut production is concentrated in Asia and Africa, where it is mostly grown under rain-fed conditions with limited external inputs (Ibrahim *et al.*, 2012). Nigeria is the third world producer of the crop, after China and India (FAO, 2017). According to Singbo *et al.*, 2016, depending on the variety, the oil content of the crop varies between 48 and 50%, and protein content is estimated at between 26 and 28% and between 11 and 27% micronutrients (carbohydrates, minerals, and vitamins). The crop is commonly consumed by roasting/boiling and processed into oil by small-scale farmers and city dwelling women for domestic use and/or cash income generation. Like other legumes, groundnut is known to be a nitrogen accumulator an attribute that makes it feasible for resource-limited farmers to save expenses on organic fertilizers. Its haulms and cake are rich in digestible crude protein and used as feed for ruminant livestock in the dry season in many countries of West and Central Africa (WCA).

Despite being one of the leading producers of sorghum, millet and groundnut, Nigeria's demand for these commodities exceeds the supplies and the deficit is met by imports from neighbouring countries (NAERLS, 2011; Vabi *et al.*, 2019). With the increase in Nigeria's population from the current approximate population of 170 million to 310 million by 2050 (Akinyemi, 2014), the demand is going to increase even further. This is due to the facts that the average yields for sorghum, millet and groundnut are quite low compared to the world average. The major limiting factors to production in Nigeria include climate variability (especially drought and high temperature), low soil nutrient level particularly nitrogen and phosphorus, infestation by parasitic weeds such as *Striga* for millet and sorghum and *Alectra* for groundnut (Echekwu *et al.*, 2012). Other limitations to high production include poor management practices such as inappropriate sowing time, limited use of inputs especially fertilizer and improved seeds. Therefore, improving and sustaining crop productivity is a critical need in Nigeria, and this will mostly occur in the Sudan and Guinea savannah regions where yield potential is much higher than in the forest due to low solar radiation and high humidity.

To address these constraints and improve crop production in Nigeria, ICRISAT in collaboration with national partners have developed improved varieties of groundnut, millet, and sorghum that are tolerant to drought, heat stress, pest and diseases along with complementary agronomic management practices such as right fertilizer, optimum fertilizer rates and sowing windows in order to improve yields at farm level. Dissemination of these technologies to farmers is being channelled through field-testing and demonstrations, provision of advisory services on crop management and storage, and organization of farmers' field schools, field days and radio shows. A project, Integrated Agriculture Activity funded by the USAID in northeast Nigeria seeks to disseminate improved crop varieties and complementary technologies in Adamawa and Borno States. This would require information on the most suitable crop varieties for targeted LGAs in the States. To provide such information would require evaluation of these varieties in combination with a range of improved crop production technologies across several locations and LGAs. However, these traditional methods of technology evaluation are largely site-specific and do not take into consideration variability in soils and climate conditions outside the areas where the technologies are tested. To assess the performance of these technologies on a large scale would require time consuming and expensive large-scale experiments across crop-growing regions like the savannas in northern Nigeria.

Hence, crop-climate models can help with the interpretation of experimental data and, after careful calibration and validation, can be used in a prospective way in conjunction with field data to draw recommendations for improved climate-induced risk adaptation strategies (Akinseye *et al.,* 2017; 2020). Cropping system simulation models such as DSSAT-Decision Support System for Agricultural Technology Transfer (Jones *et al.,* 2003), APSIM- Agricultural Production Systems sIMulator (Holzworth *et al.,* 2014) framework or SAMARA (Dingkuhn *et al.*, 2011) model provide a very important opportunity for extrapolating short-duration field experimental results to other years and other locations making use of long-term weather and soil information. To be able to make site-specific recommendations for adapted crop varieties, planting window, and crop management practices in Adamawa and Borno States, we calibrated and validated the APSIM using experimental data collected from a similar agroecological zone in northern Nigeria. The model is widely used to test the many combinations of production options and interventions under current and future climatic conditions, by many researchers across locations and found good correlations between observed and simulated values for a wide range of experimental practices against field data and environmental conditions.

4.2. Calibration, evaluation and application of the APSIM model to simulate the performance of sorghum varieties in selected communities in Adamawa and Borno States

4.2.1. Methodology

4.2.1.1. Model calibration (experiments, processes of model calibration)

Experimental data used for the calibration were principally generated from on-station field experiments conducted between 2016 and 2018 across two agroecological zones (Abuja, in the southern Guinea savanna and Kano in the Sudan savannah) in northern Nigeria. Data were collected for five contrasting sorghum cultivars which included ICSV-400 (early maturing, low photoperiod sensitive); Improved Deko (medium maturing, low photoperiod sensitive); Samsorg-44 & CSR01 (medium maturing and medium photoperiod sensitive); SK5912 (late maturing and high photoperiod sensitive) grown under semi-arid conditions. The daily weather records were obtained from the automatic weather station installed within a 2-km radius of the experiment for the corresponding years, which 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 recorded and used for model setup. The soil parameters were derived from the experimental plots, taken prior to planting. The agronomic data such as dates of flowering and maturity, yield and final biomass was obtained in the context of larger varietal characterization trials to generate cultivar-specific parameters.

APSIM-sorghum module was calibrated and evaluated within the APSIM 7.10 framework. The model APSIM requires a number of inputs for it operations, these include cultivar's name, crop management practices/information, soil properties, and daily weather records, which include rainfall, temperatures (minimum and maximum), and solar radiation. It simulates complex adaptive traits and genotype-to-phenotype prediction (Hammer, *et al.,* 2010). Crop development follows a thermal time approach with reported base (T_b), optimal (T_{opt}) and maximum (T_m) temperatures of 11, 32, and 42 ^{0}C, respectively (Carberry et al., 1993a, b). The thermal time target for the phase between emergence and panicle initiation is also a function of day length and its duration, when divided by the plastochron (^{0}C degrees per leaf), determines the total leaf number. The total leaf number multiplied by the phyllochron (^{0}Cd per leaf) determines the thermal time to reach the flag leaf stage, which is thus an emergent property of the model. The genetic coefficients were calibrated until there were appreciable agreements between measured and observed values for phenology, morphology, yield, and total dry matter (TDM) data. Thereafter, the simulated and the observed yield values used to compute different statistical skills such as mean bias error (MBE), root mean square error (RMSE), % of mean observed ($RMSE_n$) and the traditional R^2 regression statistic (least-squares coefficient of determination) respectively. $RMSE_n$ gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with an $RMSE_n$ less than 10%, good if the $RMSE_n$ is greater than 10% and less than 20%, fair if the $RMSE_n$ is greater than 20% and less than 30% and poor if the $RMSE_n$ is greater than 30% (Jamieson et al., 1991).

4.2.1.2. Model Validation (experiments and procedure of validation)

An independent dataset was used for model validation process. These data were obtained from on-farm demonstrations of improved sorghum technology conducted between 2013 and 2017 from different developmental project implemented by the ICRISAT on sorghum. The technologies range from varietal demonstration, seed dressing techniques, conservation agriculture (minimum tillage and conventional tillage) and fertilization strategies aiming at increasing sorghum productivity. The dataset also consists of information from on-farm varietal experiments in selected locations through an ICRISAT led breeding program. A total of 3,266 observed yield spread across four (4) agroecological zones in Nigeria were obtained including basic agronomic practices such as sowing date, fertilizer application rate and reference geographical coordinates either at LGA or community levels for the selected calibrated five (5) cultivars (Akinseye et al., 2020).

In addition, weather data were sourced using the downscaled CHIRPS rainfall at 5.5km resolution, and then merged with NASA Power (temperature and solar radiation as required by APSIM model. Two sources of soil information were obtained for soil parametrization. The first was obtained from field measured soil characteristics that combined the reconnaissance soil survey of Nigeria reported in 1990 and soil survey by TAMASA project in Kano, Kaduna, and Kastina States respectively. Meanwhile, the second soil data source was downscaled ISRIC (International Soil Reference and Information Centre) soil grids data with layers depth (in cm) being 5, 15, 30, 60, 100, 200. Furthermore, R scripts were developed to (i) append Chirps and NASA power data together, and convert each location into a format readily ingestible by APSIM; (ii) remap ISRICS gridded soil from 5cm to 15cm for the top soil layer as required by APSIM, then converted these soils into APSIM .SOIL readable format. The calibrated cultivar-specific coefficients were used to run the model for each variety. The difference between the model simulated and field- observed data was evaluated for grain yield using statistical skills such as mean bias error (MBE), root mean square error (RMSE), % of mean observed ($RMSE_n$) and the traditional R^2 regression statistic (least-squares coefficient of determination) respectively. $RMSE_n$ gives a measure (%) of the relative difference of simulated versus observed data.

4.2.1.3. Model application/ seasonal analysis

The long-term (1985-2010) climatic data were used to simulate grain yield and total dry matter of the sorghum varieties across the sites in both States. The simulation was applied over a 26-year period (1985-2010) at varying planting window using the recommended fertilizer rates (NPK 60:30:30) and planted at 75 cm inter-row by 30 cm intra-row spacing. For all cultivars, the model was set to consider four (4) planting windows implemented in APSIM: May 15 – May 31, Jun 1-Jun 15, Jun16- Jun 30, Jul 1- Jul 15 respectively. The cumulative rainfall at sowing was set 20 mm in 3 rainy events and implemented across all the selected sites. A compound fertilizer (NPK 15:15:15) was used in the model to supply 30 kg each of N, P_2O_5, and K_2O ha^{-1} at sowing (DAS) while the Urea (46 % N) was used to supply the top-dressing application of 30 kg N ha^{-1}) at 30 DAS. Generally, sowing was done at a soil depth of 5 cm, with a sowing density of 4.5 plants/m^2. Having completed the simulation run, mean grain yield and deviations from mean were statistically computed to assess the performance of each cultivar across the planting window and sites.

4.2.2. Results

4.2.2.1. *APSIM-Sorghum calibration and validation*

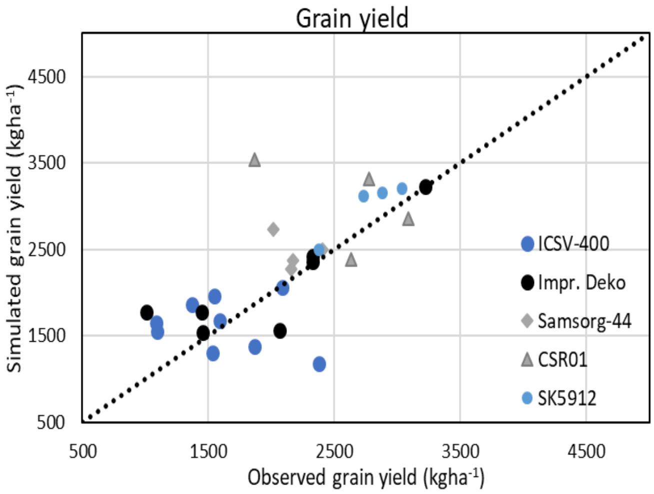
Table 1 shows that APSIM accurately simulated phenology (days to 50% flowering and maturity) with respective mean bias error (MBE) of -3.9 to 3.5 days and 1.2 to 2.4 days, while RMSE (absolute value and % of the mean observed) confirmed the robustness of the predictions. The model adjustment of leaf appearance rate for leaf ligules help to get accurate total leaf number (TLN) per plant, close to the observed mean. The model estimated TLN with MBE of 1-5 leaves per plant and relative RMSE ranging from high accuracy (6.4% for improved Deko) to low accuracy (26.2% for Samsorg-44). Similar results were earlier associated to model inability to capture the early growth stage of the crop (Akinseye et al., 2017). Grain yield and total biomass were acceptably simulated for the five cultivars within the bounds of statistical error (Fig. 1). ICSV-400 featured the lowest MBE of 50 kg ha^{-1} followed by improved Deko (114 kg ha^{-1}). CSR01 displayed the highest MBE (436 kg ha^{-1}). Relative RMSE ranged from high accuracy for SK5912 (9.2%) to very low accuracy for CSR01 (34.5%). Similarly, for total biomass, relative RMSE ranged from high accuracy for SK5912 (6.9%) to very low accuracy for improved Deko (36.8%).

Figure 2 depicts model validation against the 2013-2017 on-farm yield data, indicating better performance for grain yield of medium and late maturing cultivars (Samsorg-44, CSR01, and SK5912). Model overestimated the grain yield for ICSV-400 and Improved Deko which could be associated with low yield recorded from on-farm yield of $\leq$ 2000 kg ha^{-1} against the potential yield of 2500-3500 kg ha^{-1} for ICSV400 and 3500-4000 kg ha^{-1} for Improved Deko, under good management practices. APISM thus demonstrated robust predictions of phenology (flowering, maturity) and variable predictions of growth (TLN, grain yield and total biomass) for the five sorghum cultivars of interest. By estimating crop phenology accurately, the model will be able to capture all genotypic variations, which affect the leaf area development, biomass production, and grain yield.

Table 4.1 APSIM model evaluation for simulated phenological development and total leaf number (TLN) of contrasting sorghum cultivars calibrated under different planting dates in two agroecological zones (Sudan and Southern Guinea Savannah).

Cultivar / parameters	**Unit**	**N**	**MBE**	**RMSE**		**Observed range**	**Observed mean**
				Absolute value	**% of mean observed**		
ICSV-400- Early maturing and low photoperiod sensitivity							
50% Flowering	DAP	9	-0.7	3.4	4.9	63 - 75	69
Physiological Maturity	DAP	9	1.9	3.9	3.8	92 - 106	98
Total Leaf number		4	3.4	3.5	20.5	16 - 18	17
Improved Deko -Medium maturing, low photoperiod sensitivity							
50% Flowering	DAP	7	-3.9	6.6	7.9	75 95	84
Physiological Maturity	DAP	7	1.2	5.5	5.0	107 - 122	110
Total Leaf number		4	0.4	1.2	6.4	16 -19	18
Samsorg-44-Medium maturing, medium photoperiod sensitivity							
50% Flowering	DAP	4	0.9	3.0	3.0	85 -114	99
Physiological Maturity	DAP	4	2.4	4.0	3.2	112-140	126
Total Leaf number		4	5.1	5.2	26.2	19 -23	20
CSR01-Medium maturing, medium photoperiod sensitivity							
50% Flowering	DAP	4	1.6	2.7	2.7	84 -112	98
Physiological Maturity	DAP	4	1.9	3.1	2.4	115 -143	129
Total Leaf number		4	4.0	4.1	19.5	19 -24	21
SK5912-late maturing, high photoperiod sensitivity							
50% Flowering	DAP	4	3.5	4.7	4.4	95 -122	108
Physiological Maturity	DAP	4	2.0	4.1	3.0	122 -149	135
Total Leaf number		4	3.8	4.0	17.6	20.4-25.4	23

***MBE =** positive implies over-simulated mean observed; negative implies under-simulated the mean observed value*



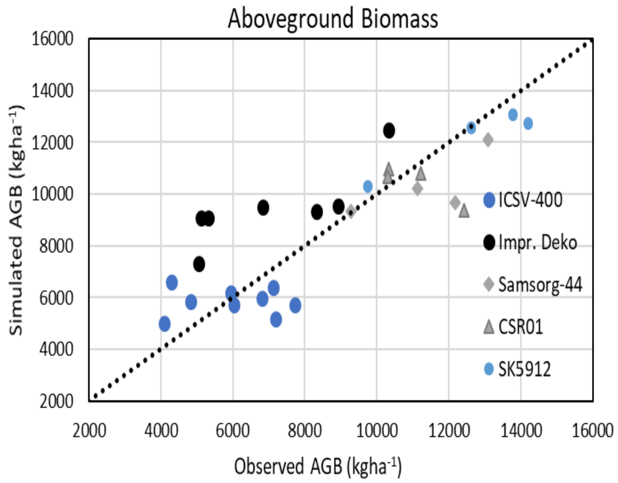


Fig. 4.1a Observed vs. simulated grain yield using experiment conducted 2016-2018 growing seasons for cultivars ranged from early to late maturing. *ICSV-400 (MBE =5.0 kgha^{-1};RMSE =532kgha^{-1},RMSEn =33.7%); Improved Deko (MBE= 114 kgha^{-1},RMSE = 370 kgha^{-1},RMSEn =18.7%); Samsorg-44 (MBE= 279 kgha^{-1};RMSE = 377 kgha^{-1},RMSEn =17.2%);CSR01 (MBE= 436 kgha^{-1},RMSE = 896 kgha^{-1},RMSEn =34.5%);SK5912 (MBE= 234 kgha^{-1};RMSE = 254 kgha^{-1}, RMSEn* ***= 9.2%)***

Figure 4.1b Observed vs. simulated total biomass using experiment conducted 2016-2018 growing seasons for cultivars ranged from early to late maturing. *ICSV-400 (MBE =149kgha^{-1}, RMSE = 1353kgha^{-1},RMSEn =22.5%); Improved Deko (MBE=2344 kgha^{-1},RMSE = 2621 kgha^{-1},RMSEn =36.8 %); Samsorg-44 (MBE= 1100 kgha^{-1};RMSE = 1432 kgha^{-1},RMSEn =12.5%);CSR01 (MBE= -615 kgha^{-1},RMSE = 1583 kgha^{-1},RMSEn =14.3%);SK5912 (MBE= -429kgha^{-1};RMSE = 868 kgha^{-1}, RMSEn = 6.9 %)*

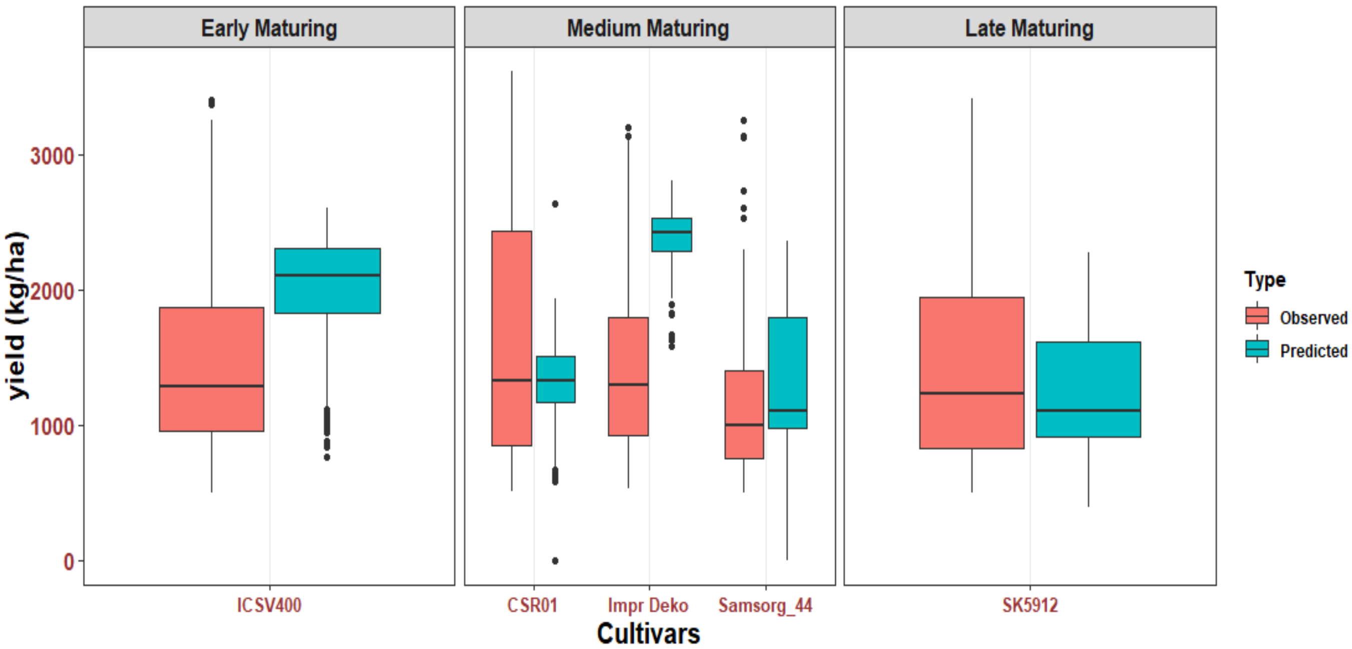


Fig. 4.2 Yield variability between Observed and simulated using on-farm data 2013-2017 growing seasons from contrasting environment for five (5) sorghum cultivars ranged from early to late maturing. *ICSV-400 (N=1192; MBE = 535 kgha^{-1};RMSE =971kgha^{-1}); Improved Deko (N=300; MBE= -960 kgha^{-1},RMSE = 1169 kgha^{-1}); Samsorg-44 (N=100; MBE= 102 kgha^{-1};RMSE = 912 kgha^{-1});CSR01 (N=944; MBE= -228kgha^{-1},RMSE = 867 kgha^{-1}); SK5912 (N=731; MBE= -219 kgha^{-1};RMSE = 839 kgha^{-1}. N= number of observations*

4.2.2.2. Sorghum-seasonal analysis

Results of seasonal analysis for mean grain yield simulated under water-limited condition across different planting windows (PW1- PW4) and locations by APSIM model over a 26-year period (1985-2010) are presented in Table 2 and 3 for Adamawa and Borno States. In both States, the planting window and sites had a significant effect on potential grain yield simulated for all the five (5) cultivars. Across the sites in both States, mean grain yield slightly decreased from PW1 to PW4. The result suggests approximately 45 days planting window (15th May and 30th June) for sorghum crops in the areas. Among the cultivars, early and medium maturing sorghum cultivars (ICSV400, Improved Deko, CSR01, and Samsorg44) simulated mean grain yield that was higher than that of the late-maturing cultivar (SK5912) in most sites. As shown in Table 2 (Adamawa State), the adapted cultivars based on the potential mean grain yield *(~2000 kg ha^{-1} threshold*) were ICSV400, Improved Deko, CSR01, and Samsorg44. These cultivars were found to be suitable for cultivation in most sites simulated except for ICSV400 in Fufore- Yola-south LGA; Daneyel-Girei, and Numan LGAs for Improved Deko; Daneyel-Girei, Guyaku-Gombi,HushereZum, Hong, Bare-Numan, Lakati-Libbo, Sheleng for CSR01 and Samsorg44). In addition, the late-maturing cultivar (SK5912) was adapted to only 10 out of 18 sites with potential mean grain yield of ~2000 kg ha^{-1} threshold (Table 4a). The coefficient of variation (CV) was lower among the sites for ICSV400 (6.3 to 8.8%) and Improved Deko (6.1- 6.8%) compared to high CV (%) simulated for CSR01, Samsorg44, and SK5912. In Table 3 (Borno State), the adapted cultivars based on the potential mean grain yield (~2000 kg ha^{-1} threshold) were ICSV400 (early maturing) and Improved Deko (medium maturing) and are found to be suitable for cultivation in most sites simulated. The varieties CSR01 and Samsorg44 were found to be adapted to 46 % (7 out of 15 simulated sites) while SK5912 was adapted to 20% of the simulated sites. Similarly, the coefficient of variation (CV) was significantly lower across the sites for ICSV400 (5.5 to 8.6%) and Improved Deko (5.1- 6.5%) compared to high CV (%) simulated for CSR01, Samsorg44, and SK5912 respectively.

Based on the simulated potential yield outputs, we therefore, recommend only early and medium maturing cultivars such as ICSV400, Improved Deko, CSR01 and Samsorg44 respectively for dissemination for most sites in Adamawa and Borno States. Also, dissemination of late-maturing cultivar, SK5912 in the region should not be encouraged for all sites/LGAs for which the model simulated below 2000 kgha^{-1} while the other sites simulated ≥ 2000 kgha^{-1} should adopt only early planting (PW1&PW2) for better productivity in both State.

Table 4.2 Simulated grain yield (kg ha^{-1}) of sorghum cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Adamawa State, northeast Nigeria.

LGA	Site	PW1	PW2	PW3	PW4	Mean	DM	PW1	PW2	PW3	PW4	Mean	DM
		ICSV-400- Early maturing and low photoperiod sensitivity						**Improved Deko -Medium maturing, low photoperiod sensitivity**					
Demsa	Mbula Kuli	2164	2276	2259	2247	**2237**	**193**	2146	2165	2175	2219	**2176**	**151**
Girei	Wuroahi	2621	2528	2474	2426	**2512**	**167**	2471	2380	2339	2369	**2390**	**131**
Girei	Daneyel	2155	2062	1962	1935	**2028**	**144**	2072	1944	1891	1875	**1945**	**130**
Yola North	Yelwa -Jambore	2192	2185	2117	2123	**2154**	**148**	2188	2098	2070	2113	**2117**	**132**
Gombi	Guyaku	2357	2261	2116	1956	**2172**	**205**	2246	2118	2005	1907	**2069**	**175**
Gombi	Tawa	2580	2486	2400	2368	**2458**	**146**	2424	2339	2265	2286	**2328**	**124**
Guyuk	Chikila	2518	2430	2329	2332	**2402**	**203**	2398	2327	2285	2315	**2331**	**159**
Guyuk	Lakumna	2538	2440	2327	2349	**2414**	**204**	2412	2336	2296	2334	**2344**	**159**
Hong	Dulmava	2366	2409	2336	2340	**2363**	**282**	2384	2272	2255	2293	**2301**	**120**
Hong	Hushere Zum	2290	2220	2126	2084	**2180**	**143**	2184	2091	2024	2018	**2079**	**197**
Yola South	Fufore	1225	1268	1343	1389	**1306**	**104**	1110	1140	1200	1210	**1165**	**75**
Numan	Bare	1887	2082	1902	1833	**1926**	**241**	1913	1964	1575	1761	**1803**	**287**
Numan	Kodomti	2008	2094	2051	2089	**2060**	**143**	1950	1971	2000	2048	**1992**	**129**
Song	Suktu	2378	2335	2279	2266	**2314**	**113**	2275	2205	2185	2217	**2221**	**106**
Shelleng	Lakati_Libbo	2108	2184	2113	2087	**2123**	**168**	2074	2077	2037	2041	**2057**	**138**
Shellenge	Jonkolo - Lama	2134	2225	2236	2239	**2208**	**197**	2095	2116	2149	2203	**2141**	**164**
Song	Sabon Gari	2617	2521	2438	2403	**2495**	**157**	2460	2348	2299	2331	**2360**	**128**
Demsa	Demsa-Nassarawo	2459	2364	2249	2248	**2330**	**168**	2299	2208	2171	2200	**2220**	**139**
Mean		**2255**	**2243**	**2170**	**2151**			**2172**	**2117**	**2068**	**2097**		
Deviation from mean		**200**	**127**	**138**	**135**			**143**	**112**	**141**	**128**		
Coefficient of variation (%)		**8.9**	**5.7**	**6.4**	**6.3**			**6.6**	**5.3**	**6.8**	**6.1**		
		CSR01-Medium maturing, medium photoperiod sensitivity						**Samsorg44-Medium maturing, medium photoperiod sensitivity**					
Demsa	Mbula Kuli	2708	2664	2660	2710	**2685**	**186**	2371	2342	2354	2396	**2366**	**158**
Girei	Wuroahi	3788	3733	3665	3520	**3676**	**273**	3378	3360	3312	3191	**3310**	**207**
Girei	Daneyel	2091	1821	1683	1634	**1807**	**410**	1848	1625	1508	1480	**1615**	**330**
Yola North	Yelwa -Jambore	2425	2226	2169	2286	**2276**	**413**	2126	1978	1917	2045	**2017**	**345**
Gombi	Guyaku	1615	1458	1250	1161	**1371**	**319**	1509	1371	1181	1123	**1296**	**259**
Gombi	Tawa	3188	3101	3089	3128	**3127**	**139**	2796	2750	2732	2734	**2753**	**126**
Guyuk	Chikila	3767	3384	2885	2574	**3152**	**717**	3400	3127	2696	2434	**2914**	**603**
Guyuk	Lakumna	2138	3620	3556	3483	**3199**	**756**	3418	3322	3272	3181	**3298**	**447**
Hong	Dulmava	2401	2388	2178	2030	**2249**	**515**	2140	2092	1944	1828	**2001**	**405**

Hong	Hushere Zum	2024	1825	1638	1619	**1777**	**356**	1790	1636	1479	1490	**1599**	**260**
Yola South	Fufore	1047	1028	1002	965	**1010**	**129**	1005	981	968	930	**971**	**120**
Numan	Bare	1575	1283	1102	1115	**1269**	**362**	1417	1182	1042	1056	**1174**	**288**
Numan	Kodomti	2217	2283	2307	2397	**2301**	**245**	1961	1996	2028	2110	**2024**	**194**
Song	Suktu	2896	2824	2846	2931	**2874**	**152**	2548	2492	2523	2588	**2538**	**127**
Shelleng	Lakati_Libbo	2115	1976	1860	1867	**1954**	**369**	1870	1751	1659	1694	**1743**	**285**
Shellenge	Jonkolo - Lama	2823	1934	2895	2975	**2657**	**448**	2500	2526	2584	2645	**2564**	**138**
Song	Sabon Gari	3414	3353	3358	3422	**3387**	**140**	3034	2977	2978	3006	**2999**	**122**
Demsa	Demsa-Nassarawo	3105	3019	3006	3066	**3049**	**178**	2771	2673	2666	2719	**2707**	**146**
Mean		**2519**	**2440**	**2397**	**2382**			**2327**	**2232**	**2158**	**2147**		
Deviation from mean		**254**	**272**	**296**	**287**			**225**	**219**	**240**	**237**		
Coefficient of variation (%)		**10.1**	**11.2**	**12.3**	**12.1**			**9.7**	**9.8**	**11.1**	**11.1**		
		SK5912-late maturing, high photoperiod sensitivity											
Demsa	Mbula Kuli	2708	1947	1827	1701	**2046**	**465**						
Girei	Wuroahi	3521	3260	2649	2226	**2914**	**618**						
Girei	Daneyel	1436	1285	1122	1084	**1232**	**263**						
Yola North	Yelwa -Jambore	1679	1539	1368	1367	**1488**	**297**						
Gombi	Guyaku	1195	1059	932	923	**1030**	**169**						
Gombi	Tawa	2482	2414	2191	2011	**2275**	**346**						
Guyuk	Chikila	3287	2463	1680	1245	**2169**	**990**						
Guyuk	Lakumna	3560	2990	2567	2278	**2849**	**683**						
Hong	Dulmava	1642	1527	1440	1289	**1476**	**349**						
Hong	Hushere Zum	1365	1259	1155	1145	**1231**	**142**						
Yola South	Fufore	917	883	824	820	**861**	**115**						
Numan	Bare	1149	974	864	874	**965**	**185**						
Numan	Kodomti	1612	1610	1544	1520	**1572**	**257**						
Song	Suktu	2165	2136	1970	1868	**2035**	**313**						
Shelleng	Lakati_Libbo	1446	1343	1235	1229	**1313**	**180**						
Shellenge	Jonkolo - Lama	2313	2342	2149	1942	**2186**	**312**						
Song	Sabon Gari	2903	2833	2698	2542	**2744**	**338**						
Demsa	Demsa-Nassarawo	2601	2543	2356	2280	**2445**	**313**						
Mean		**2110**	**1911**	**1698**	**1575**								
Deviation from mean		**251**	**271**	**272**	**273**								
Coefficient of variation (%)		**11.9**	**14.2**	**16**	**17.3**								

DM: *Deviation from mean;* ***PW1-*** *Planting window 1 (15th -31st May);* ***PW2-*** *Planting window 2(1st -15th June);* ***PW3-*** *Planting window 3 (16th -30th June);* ***PW4-*** *Planting window 4 (1st -15th July)*

Table 4.3 Simulated grain yield (kg ha^{-1}) of sorghum cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Borno State, northeast Nigeria.

LGA	Site	PW1	PW2	PW3	PW4	Mean	DM	PW1	PW2	PW3	PW4	Mean	DM
		ICSV-400- Early maturing and low photoperiod sensitivity						**Improved Deko -Medium maturing, low photoperiod sensitivity**					
Bayo	Balbaya	2302	2284	2208	2149	**2236**	**144**	2192	2159	2106	2071	**2132**	**125**
Bayo	Briyel	2196	2217	2203	2214	**2208**	**144**	2109	2092	2122	2151	**2118**	**122**
Bayo	Jara-Dali	1996	2090	2145	2135	**2092**	**147**	1989	2049	2082	2088	**2052**	**127**
Biu	Buratai	2375	2333	2251	2200	**2290**	**120**	2186	2144	2106	2083	**2130**	**105**
Biu	Kwaya Bura	2701	2666	2603	2575	**2636**	**163**	2517	2473	2462	2466	**2480**	**135**
Biu	Mathau	2103	2024	1933	1992	**2013**	**113**	1942	1851	1826	1925	**1886**	**111**
Biu	Tum	2114	2165	2189	2162	**2157**	**124**	2081	2100	2100	2112	**2098**	**109**
Hawul	Kwajaffa	2389	2346	2295	2281	**2328**	**117**	2267	2208	2188	2221	**2221**	**103**
Hawul	Puba Vidau	2160	2189	2166	2111	**2157**	**112**	2056	2067	2044	1938	**2026**	**143**
Hawul	Sakwa Hema	2369	2332	2237	2231	**2292**	**126**	2252	2184	2138	2145	**2180**	**109**
Kwaya-Kusar	Bila Gusi	2133	2161	2103	2107	**2126**	**146**	2058	2036	2031	2051	**2044**	**121**
Kwaya-Kusar	Kurbo Gayi	2745	2710	2646	2590	**2673**	**168**	2558	2515	2492	2470	**2509**	**137**
Shani	Gwaskara	2554	2535	2450	2453	**2498**	**129**	2419	2362	2344	2361	**2372**	**118**
Shani	Kubo	2485	2466	2330	2341	**2406**	**202**	2391	2339	2307	2306	**2336**	**162**
Shani	Lakundum	2322	2302	2243	2238	**2276**	**115**	2171	2148	2137	2146	**2151**	**107**
Mean		**2330**	**2321**	**2267**	**2252**			**2213**	**2182**	**2166**	**2169**		
Deviation from mean		**200**	**127**	**138**	**135**			**143**	**112**	**141**	**128**		
Coefficient of variation (%)		**8.6**	**5.5**	**6.1**	**6**			**6.5**	**5.1**	**6.5**	**5.9**		
		CSR01-Medium maturing, medium photoperiod sensitivity						**Samsorg44-Medium maturing, medium photoperiod sensitivity**					
Bayo	Balbaya	1741	1506	1332	1290	**1467**	**321**	1587	1407	1252	1228	**1368**	**248**
Bayo	Briyel	2077	2059	1982	1814	**1983**	**333**	1849	1856	1774	1656	**1784**	**243**
Bayo	Jara-Dali	2021	1955	1567	1289	**1708**	**456**	1806	1754	1434	1188	**1545**	**366**
Biu	Buratai	2825	2750	1929	2719	**2555**	**411**	2503	2433	2358	2411	**2426**	**191**
Biu	Kwaya Bura	3333	3455	3393	3546	**3432**	**232**	3431	3390	3290	3185	**3324**	**185**
Biu	Mathau	1152	1135	1048	959	**1074**	**135**	1099	1081	1024	940	**1036**	**110**
Biu	Tum	2399	2145	1639	1125	**1827**	**701**	2112	1891	1491	1048	**1636**	**590**
Hawul	Kwajaffa	2254	2104	1373	698	**1617**	**821**	1992	1880	1265	593	**1442**	**725**
Hawul	Puba Vidau	1990	1322	459	254	**1006**	**926**	1822	1208	424	238	**923**	**861**
Hawul	Sakwa Hema	2062	1976	1845	1759	**1910**	**260**	1857	1772	1675	1649	**1738**	**194**
Kwaya-Kusar	Bila Gusi	2403	2341	2294	2262	**2325**	**254**	2125	2062	2021	2007	**2054**	**203**
Kwaya-Kusar	Kurbo Gayi	3722	3669	3644	3546	**3645**	**218**	3313	3276	3242	3157	**3247**	**179**
Shani	Gwaskara	3113	2999	2873	2844	**2957**	**235**	2728	2641	2515	2482	**2592**	**215**
Shani	Kubo	3736	3694	3796	3817	**3761**	**549**	3388	3362	3477	3501	**3432**	**465**
Shani	Lakundum	2671	2651	2586	2609	**2629**	**232**	2331	2318	2281	2289	**2305**	**183**

Mean		**2500**	**2384**	**2117**	**2035**		**2263**	**2155**	**1968**	**1838**
Deviation from mean		**288**	**323**	**322**	**323**		**231**	**270**	**277**	**273**
Coefficient of variation (%)		**11.5**	**13.5**	**15.2**	**15.9**		**10.2**	**12.5**	**14.1**	**14.8**
		SK5912-late maturing, high photoperiod sensitivity								
Bayo	Balbaya	1220	1086	991	979	**1071**				
Bayo	Briyel	1538	1486	1362	1251	**1409**				
Bayo	Jara-Dali	1441	1275	834	556	**1026**				
Biu	Buratai	2162	2033	1793	1612	**1900**				
Biu	Kabura	3339	3075	2444	2080	**2734**				
Biu	Mathau	984	925	861	591	**843**				
Biu	Tum	1543	1201	667	247	**914**				
Hawul	Kwajaffa	1510	916	210	45	**682**				
Hawul	Puba Vidau	742	1322	45	0	**544**				
Hawul	Sakwa Hema	1472	1390	1270	1219	**1339**				
Kwaya-Kusar	Bila Gusi	1794	1658	1483	1412	**1587**				
Kwaya-Kusar	Kurbo Gayi	3163	2972	2528	2152	**2704**				
Shani	Gwaskara	2185	2094	1865	1751	**1974**				
Shani	Kubo	3806	3441	2990	2764	**3250**				
Shani	Lakundum	1892	1851	1714	1653	**1778**				
Mean		**1919**	**1782**	**1404**	**1221**					
Deviation from mean		**268**	**332**	**272**	**250**					
Coefficient of variation (%)		**14**	**18.7**	**19.4**	**20.5**					

DM: *Deviation from mean;* ***PW1-*** *Planting window 1 (15th -31st May);* ***PW2-*** *Planting window 2(1st -15th June);* ***PW3-*** *Planting window 3 (16th -30th June);* ***PW4-*** *Planting window 4 (1st -15th July)*

4.3. Calibration, evaluation and application of the APSIM model to simulate the performance of millet varieties in selected communities in Adamawa and Borno States

4.3.1. Methodology

4.3.1.1. Experiments for model calibration and evaluation

Experimental data used for calibration and evaluation of the APSIM model were generated from two locations during 2017 growing seasons in the Sudan savannah zone of Nigeria. The first location was ICRISAT Research field situated within Institute for Agricultural Research in Wasai, Minjibir Local Government Area, Kano State (Latitudes 12.17°N and longitude 8.65°E). The second location was ICRISAT experimental site on a farmer`s field at Gambawa, Gumel Local Government Area, Jigawa State (Latitude 12.98 °N and Longitude 9.75°E). Weather data for the trial conducted at Minjibir research station were collected from the ICRISAT Meteorological station adjacent to the experiment plot. Gambawa weather data were obtained from the Jigawa Agricultural and Rural Development Authority (JARDA), Gumel office (about 10 km from the plot). The meteorological data reported include daily rainfall, minimum temperature, maximum temperature and number of rainy days (NRD). Both sites have a mono-modal rainfall pattern; most of the rain in the area comes as short-duration, high-intensity storms between June and September with one or two rainfall events in October. About 70% of the total rainfall is received between July and August during the growing season. The soils in the two locations were sandy soil characterized by less than 10% clay and silt and more than 88% sand. They were generally acidic with soil pH range from 5.0 to 6.4 topsoil in Minjibir while that of Gambawa site varied from 5.4 to 6.3. Minjibir soil had slightly higher fertility status than Gambawa (Ajeigbe et al., 2019).

The experiment was established on different sowing dates (four) planted at 14-day interval and pearl millet cultivars (three) as treatments established in a randomized complete block design (RCBD) in four replications. In both locations, three improved pearl millet, which include Jirani, [extra early maturity (65-70 days], SosatC88- early maturity (80-90 days) and SuperSosat- early maturity (80-90) with higher yield than SOSAT C88 were tested. These selected cultivars are suitable for many millet producing dryland areas of Nigeria taking into consideration the major biotic and abiotic factors. The experiment protocol was designed to record dates of sowing, flowering and maturity, morphology trait, total dry matter (TDM) grain yield and yield components under non-limited nutrient supply. In Minjibir, pearl millet was sown on 6 June, 25, 8 July and 21 July, respectively while in Gambawa planting was on 5 July, 19 July, 1 August and 15 August. During land preparation, double-harrowed and ridged with tractor was used at Minjibir, meanwhile in Gambawa; land preparation was ridged with two working bulls. The plant population was approximately 26,667 hills/ha (0.75 m between rows and 0.50 m between hills), which was achieved by thinning to 2 plant/hill, 15-20 days after planting (DAP). The crop was fertilized using recommended application rate of NPK 60:30:30 which implies 200 kg/ha of NPK15:15:15 at sowing and 65 kg/ha of Urea (46% N) at 28-30 DAP. Insecticides were used according to local recommendations and weeding was done manually.

4.3.1.2 Model calibration and evaluation

The calibration and evaluation were implemented within the APSIM 7.10 framework using APSIM-millet module. The module requires several inputs for its operations, these include cultivar's name, crop management practices/information, soil properties and daily weather records, which include rainfall, temperatures (minimum and maximum) and solar radiation. It simulates complex adaptive traits and genotype-to-phenotype prediction (Hammer, *et al.,* 2010). Crop development follows a thermal time approach with reported base (Tb), optimal (Topt) and maximum (Tm) temperatures of 11, 32, and 42 ^{0}C, respectively (Carberry *et al.*, 1993a, b). The thermal time target for the phase between emergence and panicle initiation is also a function of day length and its duration, when divided by the plastochron (^{0}C degrees per leaf), determines total leaf number. Total leaf number multiplied by the phyllochron (^{0}Cd per leaf) determines the thermal time to reach flag leaf stage, which is thus an emergent property of the model. 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 that were supposed to clout the reference variable. Thereafter, the simulated and the observed yield values were evaluated with different statistical skills such as mean bias error (MBE), root mean square error (RMSE), % of mean observed ($RMSE_n$) and the traditional R^2 regression statistic (least-squares coefficient of determination) respectively. $RMSE_n$ gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a $RMSE_n$ less than 10%, good if the $RMSE_n$ is greater than 10% and less than 20%, fair if the $RMSE_n$ is greater than 20% and less than 30% and poor if the $RMSE_n$ is greater than 30% (Jamieson et al., 1991).

4.3.1.3. *Model application/seasonal analysis*

Following successful calibration and evaluation of the model, long-term (1985-2010) simulation run was used to simulate the performance of the millet varieties using the calibrated cultivar-specific parameters for all cultivars tested across the sites. The simulation was applied over a 26-year period (1985-2010) at varying planting window using the recommended fertilizer rates (NPK 60:30:30) applied in two splits. For all cultivars, the model was set to consider four (4) planting windows which include May 15 – May 31, Jun 1- Jun 15, Jun16- Jun 30, Jul 1- Jul 15 respectively and planted at 75 cm inter-row by 50cm intra-row spacing totalled 27,000 plants/ha. The cumulative of rainfall at sowing was set 20 mm in 3-rainy events and implemented across all the selected sites. A compound fertilizer (NPK 15:15:15) was used in the model to supply 30 kg each of N and P_2O_5 at sowing (DAS) as first application. Urea (46 % N) was used to supply the remaining dose (30 kg N ha^{-1}) at 30 DAS. The model was set at sowing depth of 5cm, with a sowing density of 2.7 plants/m^2. Having completed the simulation run, mean grain yield and deviations from mean were computed to assess the performance of each cultivar across the planting window and sites.

4.3.2. Results

4.3.2.1. *APSIM-millet calibration and evaluation*

Table 4 shows APSIM model evaluation for simulated phenological development (days to 50% flowering and physiological maturity) and plant height of pearl millet cultivars calibrated under different planting dates in two locations in the Sudan savanna agroecological zone. The model evaluation with the adjusted cultivar-specific parameters provided good agreement between simulated and observed values for days to 50% flowering and physiological maturity at high accuracy within the bounds of statistical error for the pearl millet cultivars tested. For days to 50% flowering, MBE ranged from -3.5 days (SuperSosat) to 1.5 days (SosatC88), RMSE values show equal to or less than 4 days among the cultivars. Time to physiological maturity was simulated with less accuracy than flowering for all the cultivars except SuperSosat possibly reflecting the additive effects of errors simulating the intermediate flowering and grain fill stages. The model slightly over-predicted the observed days to physiological maturity for Jirani and SosatC88 with MBE of 6 days, RMSE range from 3 to 7 days while $RMSE_n$ varied from 2.9 to 8.6 %. The model adjustment of plant canopy height for help to get accurate plant height to low accuracy with the observed mean. APSIM overestimated observed values across the planting dates resulting to MBE of 13.6 cm (Jirani), 62.8 cm for SosatC88 and 64.7 cm for SuperSosat, respectively while the absolute RMSE ranged from 42–73 cm.

Figure 3a shows that model slightly under-predicted the LAI indicating low accuracy in predicting LAI. The absolute RMSE ranged from 0.63 to 0.82 and coefficient of determination (R^2) indicating a strong association between the simulated and observed value varied from 0.3 to 0.5. Model comparison with observed values showed that grain yield and total dry matter (TDM) were accurately simulated among the three cultivars within the bounds of statistical error (Fig. 3b & 3c).

For grain yield (Fig.3b), SosatC88 shows the lowest MBE of 119 kg ha^{-1} followed by SuperSosat (320 kg ha^{-1}) and Jirani had the highest MBE of 432 kg ha^{-1}. The relative $RMSE_n$ indicates very low accuracy for all the cultivars ranging from 31.3 to 36.7%. Similarly, for total biomass (Fig.3c), the relative $RMSE_n$ shows low accuracy for Jirani (22.4%) followed by SosatC88 (26.5%) and SuperSosat (35.8%) respectively. The model accuracy varied from low to very low for grain yield and TDM because the observed data used did not account for individual tillering productivity that is a key parameter in the APSIM-millet module. This suggests a need for further evaluations with an independent dataset for improvement on yield and yield components.

Table 4.4 APSIM model evaluation for simulated phenological development and plant height of pearl millet cultivars calibrated under different planting dates in two locations in Sudanian agroecological zone.

Cultivar/ parameters	Unit	N	MBE	RMSE		Observed range	Observed mean
				Absolute value	% of mean observed		
Jirani							
50% flowering	DAP	8	-1.0	1.1	2.3	44 - 48	46
Physiological Maturity	DAP	8	5.5	5.7	8.6	66 -68	66
Plant height	cm	8	13.6	41.7	23.6	147 -220	191
SosatC88							
50% Flowering	DAP	8	1.5	1.9	3.2	57- 60	59
Physiological Maturity	DAP	8	6.6	7.2	8.1	87 -90	88
Plant height	cm	8	62.8	71.0	30.1	129-237	177
SuperSosat							
50% Flowering	DAP	8	-3.5	3.7	5.9	62 -65	64
Physiological Maturity	DAP	8	-0.3	2.8	2.9	94 - 96	95
Plant height	cm	8	64.7	72.9	31.6	129 -232	175

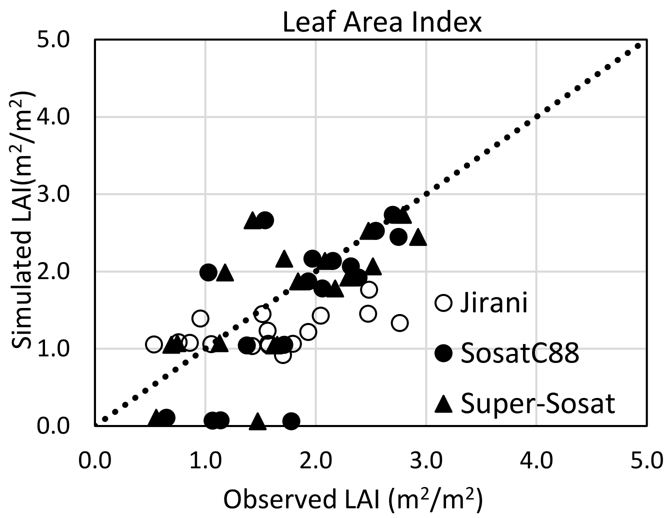


Fig. 4.3a Model simulated vs. Observed LAI using experiment conducted under different planting dates during 2017 growing seasons in two locations within Sudanian agro ecological zones. *Jirani (MBE = -0.46; RMSE =0.82, $RMSE_n$ =38.5%; R^2 =0.30); SosatC88 (MBE= 0.11, RMSE = 0.50, $RMSE_n$ = 42.1%, R^2 =0.71); SuperSosat (MBE= 0.02, RMSE = 0.63, RMSEn =36.9%, R^2 = 0.49); N= number of observation per cultivar = 20.*

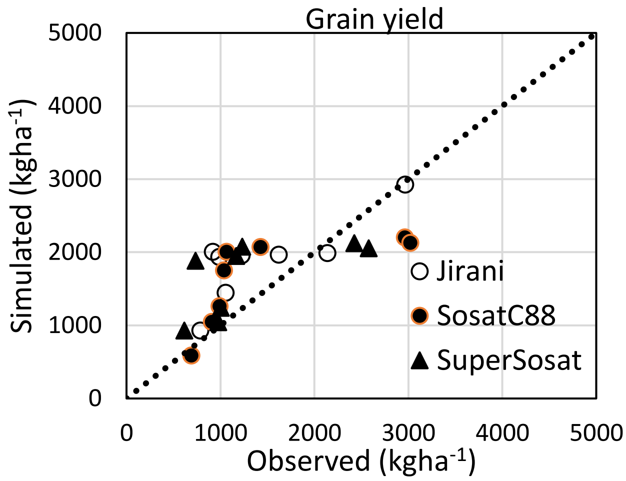


Fig. 4.3b Model simulated vs. Observed grain yield using experiment conducted under different planting dates during 2017 growing seasons in two locations within Sudanian agro ecological zones. *Jirani (MBE 432 $kgha^{-1}$, RMSE = 606 $kgha^{-1}$, $RMSE_n$ = 31.3%, R^2 =0.64); SosatC88 (MBE= 119 $kgha^{-1}$, RMSE = 642 $kgha^{-1}$, $RMSE_n$ = 32.4%, R^2 =0.50); SuperSosat (MBE= 320 $kgha^{-1}$, RMSE = 628 $kgha^{-1}$, $RMSE_n$ = 36.7% R2 =0.40); Number of observation per cultivar =*

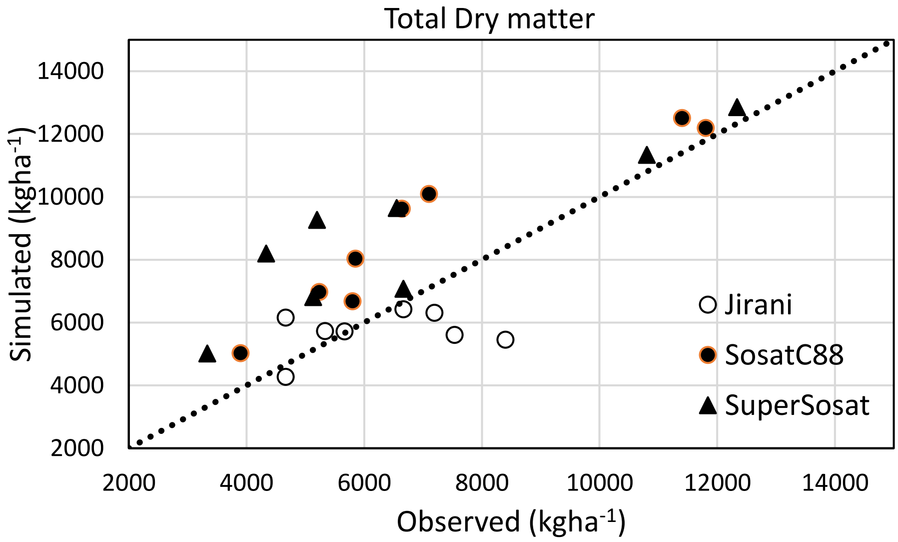


Fig. 4.3c –Model simulated vs. Observed total dry matter using experiment conducted under different planting dates during 2017 growing seasons in two locations within Sudanian agro ecological zones. *Jirani (MBE -552 $kgha^{-1}$, RMSE = 1403 $kgha^{-1}$, $RMSE_n$ = 22.4%, R^2 =0.20); SosatC88 (MBE= 1682 $kgha^{-1}$, RMSE = 1913 $kgha^{-1}$, $RMSE_n$ = 26.5 %, R^2 =0.85); SuperSosat (MBE= 1986 $kgha^{-1}$, RMSE = 2439 $kgha^{-1}$, $RMSE_n$ = 35.8% R^2 =0.77); Number of observation per cultivar =8.*

4.3.2.2. *Pearl millet - seasonal analysis*

Results of seasonal analysis for mean water-limited grain yield simulated for different planting windows (PW1- PW4) and locations by APSIM model over a 26-year period (1985-2010) are presented in Table 5 and 6 for Adamawa and Borno respectively. In both States, APSIM simulated high yield for the cultivars tested across the sites. In addition, the planting window and sites had influenced on grain yield for all three (3) cultivars simulated under water-limited environment. Across the sites, mean grain yield slightly increases from PW1 to PW3 and thereafter yield decline for PW4. The simulation outputs suggest 60 days of planting window (15th May and 15th July) for pearl millet in the selected area, given farmer's opportunity to cultivate during low rainfall year or when the onset of rain is delay. However, farmers would attain optimum yield for all cultivars when planted between PW2 (1st -15th June) and PW3 (16th -30th June) across the selected sites. As shown in Table 5 (Adamawa State), all the cultivars are suitable for cultivation in most sites simulated with some few sites simulating below 2000 kg ha^{-1}. The coefficient of variation (CV) was generally lowacross the sites from PW1 to PW4. The CV for Jirani ranged from 7.7 to 18.1%, SosatC88, 6.2- 8.3% and SuperSosat 7.0 to 9.4. In Borno State (Table 6), all three pearl millet cultivars are found suitable for all the sites simulated based on the simulated mean grain (~1500 kg ha^{-1} threshold) yield. The coefficient of variation (CV) was significantly lower across the sites with Jirani having a CV ranging from 5.9 to 12.9%, SosatC88, 4.8- 6.0% and SuperSosat 5.4 – 6.8 % respectively. Based on the simulated outputs, the three pearl millet cultivars tested are therefore recommended for dissemination, however, farmers should be guided to maximize the optimum-planting window (PW2 & PW3) and use the recommended fertilizer inputs for higher productivity.

Table 4.5 Simulated grain yield (kgha^{-1}) of pearl millet cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Adamawa State, northeast Nigeria.

LGA	Site	PW1	PW2	PW3	PW4	Mean	DM	PW1	PW2	PW3	PW4	Mean	DM
				Jirani						**SosatC88**			
Demsa	Mbula Kuli	2355	3086	3123	2585	**2787**	**495**	2434	2924	2973	2519	**2713**	**310**
Girei	Wuroahi	2577	3430	3479	2901	**3096**	**555**	2892	3432	3522	2911	**3189**	**366**
Girei	Daneyel	2117	2306	2012	1536	**1993**	**407**	2065	2257	2079	1682	**2021**	**271**
Yola North	Yelwa -Jambore	1976	2381	2306	1857	**2130**	**351**	2066	2428	2347	1959	**2200**	**275**
Gombi	Guyaku	2264	2480	2162	1560	**2116**	**412**	2191	2341	2160	1653	**2086**	**308**
Gombi	Tawa	2833	3283	3244	2623	**2996**	**368**	2861	3243	3164	2674	**2985**	**257**
Guyuk	Chikila	2892	3494	3423	2796	**3151**	**489**	3200	3916	3771	2733	**3405**	**638**
Guyuk	Lakumna	2803	3333	3444	2870	**3113**	**446**	3111	3867	3933	2930	**3460**	**604**
Hong	Dulmava	2038	2210	1949	1460	**1914**	**321**	1999	2113	1952	1565	**1907**	**250**
Hong	Hushere Zum	2437	2808	2823	2438	**2627**	**354**	2430	2714	2764	2351	**2565**	**261**
Yola South	Fufure	1841	2225	2327	2001	**2099**	**263**	1800	2101	2165	1845	**1978**	**197**
Numan	Bare	1896	2327	2081	1535	**1960**	**423**	1840	2143	1917	1499	**1850**	**306**
Numan	Kodomti	1996	2204	2045	1622	**1967**	**317**	1849	2116	2061	1702	**1932**	**220**
Song	Suktu	2285	2825	2780	2298	**2547**	**381**	2251	2639	2678	2289	**2464**	**222**
Shelleng	Lakati_Libbo	2130	2523	2247	1675	**2144**	**449**	2063	2350	2120	1692	**2056**	**300**
Shellenge	Jonkolo - Lama	2214	2862	2916	2430	**2606**	**465**	2364	2818	2887	2458	**2632**	**267**
Song	Sabon Gari	2805	3409	3443	2837	**3124**	**397**	2869	3381	3418	2948	**3154**	**274**
Demsa	Demsa-Nassarawo	2753	3308	3313	2780	**3039**	**388**	2758	3240	3357	2858	**3053**	**286**
Mean		**2345**	**2805**	**2729**	**2211**			**2391**	**2779**	**2737**	**2237**		
Deviation from mean		**424**	**209**	**248**	**171**			**198**	**174**	**190**	**186**		
Coefficient of variation (%)		**18.1**	**7.5**	**9.1**	**7.7**			**8.3**	**6.2**	**6.9**	**8.3**		
				SuperSosat									
Demsa	Mbula Kuli	2215	2654	2699	2288	**2464**	287						
Girei	Wuroahi	2693	3223	3318	2740	**2994**	352						
Girei	Daneyel	1774	1911	1723	1377	**1696**	267						
Yola North	Yelwa -Jambore	1790	2104	2005	1667	**1892**	269						
Gombi	Guyaku	1883	2001	1808	1354	**1761**	296						
Gombi	Tawa	2633	2978	2881	2433	**2731**	245						

Guyuk	Chikila	3065	3758	3631	2626	**3270**	620
Guyuk	Lakumna	2976	3711	3782	2817	**3322**	584
Hong	Dulmava	1670	1750	1588	1264	**1568**	244
Hong	Hushere Zum	2133	2374	2412	2045	**2241**	247
Yola South	Fufure	1537	1796	1843	1570	**1687**	174
Numan	Bare	1581	1809	1590	1223	**1551**	284
Numan	Kodomti	1565	1795	1723	1402	**1621**	217
Song	Suktu	1989	2332	2363	2018	**2176**	203
Shelleng	Lakati_Libbo	1781	2009	1770	1395	**1739**	293
Shellenge	Jonkolo - Lama	2135	2542	2593	2202	**2368**	245
Song	Sabon Gari	2660	3141	3177	2744	**2930**	261
Demsa	Demsa-Nassarawo	2553	3004	3110	2650	**2829**	268
Mean		**2146**	**2494**	**2445**	**1990**		
Deviation from mean		**193**	**175**	**193**	**187**		
Coefficient of variation (%)		**9.0**	**7.0**	**7.9**	**9.4**		

DM: *Deviation from mean;* ***PW1****- Planting window 1 (15th -31st May);* ***PW2****- Planting window 2(1st -15th June);* ***PW3****- Planting window 3 (16th -30th June);* ***PW4****- Planting window 4 (1st -15th July)*

Table 4.6 Simulated grain yield (kgha^{-1}) of pearl millet cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Borno State, Northeast Nigeria.

		PW1	**PW2**	**PW3**	**PW4**	**Mean**	**DM**	**PW1**	**PW2**	**PW3**	**PW4**	**Mean**	**DM**
LGA	**Site**	**Jirani**						**SosatC88**					
Bayo	Balbaya	2357	2728	2600	1998	**2421**	**374**	2305	2623	2609	2131	**2417**	**236**
Bayo	Briyel	2392	2867	2952	2495	**2677**	**276**	2409	2785	2868	2449	**2628**	**234**
Bayo	Jara-Dali	2241	2917	3034	2653	**2711**	**470**	2310	2718	2824	2405	**2564**	**279**
Biu	Buratai	2274	2406	2249	1683	**2153**	**331**	2330	2626	2538	2050	**2386**	**248**
Biu	Kwaya Bura	2967	3479	3475	3025	**3236**	**376**	3116	3552	3679	3083	**3358**	**290**
Biu	Mathau	2446	2740	2748	2372	**2577**	**226**	2211	2455	2494	2106	**2316**	**206**
Biu	Tum	2624	3034	3140	2816	**2904**	**292**	2572	2938	3122	2596	**2807**	**304**
Hawul	Kwajaffa	2874	3366	3393	2917	**3137**	**385**	2814	3206	3347	2806	**3043**	**276**
Hawul	Puba Vidau	2887	3332	3443	2857	**3130**	**391**	2497	2900	2642	1666	**2426**	**552**
Hawul	Sakwa Hema	2506	2917	2813	2435	**2668**	**312**	2487	2746	2723	2293	**2562**	**225**
Kwaya-Kusar	Bila Gusi	2269	2706	2582	2117	**2419**	**319**	2309	2611	2513	2086	**2380**	**235**
Kwaya-Kusar	Kurbo Gayi	2973	3414	3324	2752	**3116**	**337**	3031	3476	3445	2850	**3201**	**288**
Shani	Gwaskara	2718	3006	2841	2164	**2682**	**388**	2736	3019	2887	2299	**2736**	**308**
Shani	Kubo	2716	3282	3372	2837	**3052**	**432**	3270	3839	3891	3251	**3563**	**335**
Shani	Lakundum	2426	2596	2456	1947	**2356**	**300**	2284	2564	2507	2063	**2354**	**233**
Mean		**2578**	**2986**	**2962**	**2471**			**2579**	**2937**	**2939**	**2409**		
Deviation from mean		**332**	**230**	**189**	**146**			**137**	**142**	**149**	**145**		
Coefficient of variation (%)		12.9	7.7	6.4	5.9			5.3	4.8	5.1	6.0		
		SuperSosat											
Bayo	Balbaya	2050	2309	2279	1848	**2122**	**217**						
Bayo	Briyel	2159	2491	2571	2197	**2354**	**215**						
Bayo	Jara-Dali	2105	2460	2561	2186	**2328**	**252**						
Biu	Buratai	2039	2283	2191	1754	**2067**	**229**						
Biu	Kabura	2922	3326	3451	2884	**3146**	**278**						
Biu	Mathau	1941	2140	2177	1842	**2025**	**191**						
Biu	Tum	2349	2684	2873	2403	**2577**	**282**						
Hawul	Kwajaffa	2630	2997	3147	2638	**2853**	**264**						
Hawul	Puba Vidau	2341	2730	2489	1572	**2283**	**522**						
Hawul	Sakwa Hema	2243	2449	2398	2044	**2283**	**212**						

Kwaya-Kusar	Bila Gusi	2063	2314	2202	1818	**2099**	**222**
Kwaya-Kusar	Kurbo Gayi	2818	3219	3169	2601	**2952**	**278**
Shani	Gwaskara	2467	2692	2541	1992	**2423**	**308**
Shani	Kubo	3085	3636	3693	3086	**3375**	**325**
Shani	Lakundum	2035	2265	2211	1789	**2075**	**231**
Mean		**2350**	**2666**	**2663**	**2177**		
Deviation from mean		**136**	**144**	**154**	**148**		
Coefficient of variation (%)		**5.8**	**5.4**	**5.8**	**6.8**		

DM: *Deviation from mean;* ***PW1-*** *Planting window 1 (15th -31st May);* ***PW2-*** *Planting window 2 (1st -15th June);*
PW3- *Planting window 3(16th -30th June);* ***PW4-*** *Planting window 4 (1st -15th July).*

4.4. Calibration, evaluation and application of the APSIM model to simulate the performance of groundnut varieties in selected communities in Adamawa and Borno States

4.4.1 Methodology

4.4.1.1. Experiments for model calibration and evaluation

The experiments were conducted in three environments in 2014/2015 and 2016/2017 dry seasons in ICRISAT experimental plot at Wasai (Latitudes 12.17°N and longitude 8.65°E and 437 m above sea level), Minjibir Local Government Area, Kano State, Nigeria. Wasai is in the Sudan savanna region of Nigeria. The soil textural class was sandy loam comprising 81.5% sand, 2.28% silt and 5.28% clay, with pH of 6.5.

The experiments were conducted using five improved groundnut varieties which include Samnut23, Samnut24, Samnut25 and Samnut26 respectively. Samnut-23 is medium maturing variety (90-100 days), while Samnut-24, Samnut-25 and Samnut-26 are early maturing varieties with maturity periods of 80-90, 90-95 and 90-95 days respectively.

The experiments were laid out in a Split plot design with the planting dates assigned to the main plot, while varieties were assigned to the sub-plot and replicated four times in each planting date at 15 days interval from October to January. The plots were irrigated and allowed to dry for two days. It was then doubled harrowed; Phosphorus was applied at the rate of 27 kg P_2O_5 ha^{-1} and ridged at 75 cm between ridges. The plots were irrigated through furrow (surface) irrigation and planting was done by the sides of the ridges at 10 cm between hills and two seeds per hole. The plot was subsequently irrigated every 7 -10 days. Weeding was done first at three weeks after sowing, while subsequent weeding was done as per need, but at average of 3 – 4 weeks after the previous weeding. The basic agronomic parameters including days to flowering, physiological maturity, grain yield and total dry matter collected were used for model calibration and evaluation accordingly.

4.4.1.2. Model calibration and evaluation

The legume crop module of peanut was implemented for calibration and evaluation within the APSIM (APSIM7.10) framework. Four (4) cultivars grown under different sowing dates established at the Wasai experimental station, Sudan Savanna agroecological zone. Generally, input data required for the model are crop management information, cultivar specific parameters (genetic coefficient), soil properties and daily weather records.

The cultivar-specific coefficients were determined by first choosing a standard default cultivar within APSIM-peanut module and adjusting the development- and growth-related coefficients to achieve the best possible match between simulated and observed phenology, total dry matter (TDM) and grain yield available in the experimental data. Thereafter, the simulated and the observed yield values used to compute different statistical skills such as mean bias error (MBE), root mean square error (RMSE), % of mean observed ($RMSE_n$) and the traditional R^2 regression statistic (least-squares coefficient of determination) respectively. $RMSE_n$ gives a measure (%) of the relative difference of simulated versus observed data. The simulation is considered excellent with a $RMSE_n$ less than 10%, good if the $RMSE_n$ is greater than 10% and less than 20%, fair if the $RMSE_n$ is greater than 20% and less than 30% and poor if the $RMSE_n$ is greater than 30% (Jamieson et al., 1991).

4.4.1.3. Model application for long-term simulation across the selected sites

After confirming the credibility of the model, the long-term (1985-2010) simulation run was carried out for the three crops in both states; to test the model performance using the calibrated cultivar-specific parameters for all cultivars. The simulation was applied over a 26-year period (1985-2010) at varying planting window using the recommended fertilizer rates. The model was set to consider five (5) planting windows implemented in APSIM: May 15–31, June 1–15, June 16–30, July 1–15 and July 16–31, respectively. For all the crops, the cumulative of rainfall at sowing was set 20 mm in 3 rainy events and implemented across all the selected sites. A compound fertilizer (NPK 15:15:15) was used in the model to supply 30 kg each of N, P_2O_5, and K_2O ha^{-1} at sowing (DAS) as first application. Single Super Phosphate (SSP) at the rate of 18 kg P_2O_5 ha^{-1} was used to supply additional dose of P at 30 DAS. Sowing was done at a soil depth of 5 cm, with a sowing density of 6.7plamt/m^2 for groundnut. Having completed the simulation run, mean grain yield and deviations from mean were calculated to assess the performance of each cultivar across the planting window and sites.

4.4.2. Results

4.4.2.1. ***APSIM-Groundnut calibration and evaluation***

After calibration, the model was able to predict the number of days from planting to flowering and physiological maturity for the four groundnut cultivars grown under different planting dates during two cropping seasons over Sudan savanna agroecological zone (Tables 7). Phenology varied among cultivars, the mean observed days to 50% flowering ranged from 26 to 63 days and the mean observed physiological maturity ranged from 94 to 161 days. The large variations could be associated with delay in germination observed during cold weather season (harmattan) despite the availability of moisture on the field. The model evaluation with the adjusted cultivar-specific parameters provided good agreement between simulated and observed values for days to 50% flowering and physiological maturity at high accuracy within the bounds of statistical error for the groundnut cultivars tested. For days to 50% flowering, MBE ranged from -1.7 to 1.7 days, RMSE value ranged from 5 to 9 days among the cultivars. Time to physiological maturity was simulated with less accuracy than flowering for all the cultivars possibly reflecting the additive effects of errors in observed value.

The model over predicted the observed values for all the cultivars with MBE ranged from approximately 5 to 7 days and RMSE ranged from 10 to 15 days.2.9 to 8.6 %. Model comparison with observed values for grain yield and total dry matter (TDM) were also acceptably simulated among the cultivars within the bounds of statistical error (Fig. 6a & b). For grain yield (Fig.4a), Samnut26 reveal the lowest MBE of 249 kg ha^{-1} followed by Samnut24 (266 kg ha^{-1}) and Samnut23 had the highest MBE of 343 kg ha^{-1}. The relative $RMSE_n$ varied from fairly to low accuracy for all the cultivars ranged from 26.7 to 34.5%. For TDM (Fig.4b), the model over predicted the observed values for all the cultivars with MBE ranged from 533 to 1036 kg ha^{-1}, the relative $RMSE_n$ shows moderate to low accuracy with Samnut24 estimated the lowest value of 16.9 % followed by Samnut26 (20.9%) while Samnut23 and 25 recorded the highest value (23.2 and 23.8%) respectively.

Table 4.7 APSIM model evaluation for simulated phenological development (days to flowering and physiological maturity) of groundnut cultivars calibrated under different planting dates within Sudan Savanna agro ecological zone.

Cultivar/ parameters	Unit	N	MBE	RMSE	Observed range	Observed mean
Samunt23						
50% Flowering	DAP	17	-1.3	7.9	34 -63	49
Physiological Maturity	DAP	17	5.1	9.5	109 -158	136
Samunt24						
50% Flowering	DAP	17	-1.7	9.0	26 -63	45
Physiological Maturity	DAP	17	5.1	15.2	94 -158	125
Samunt25						
50% Flowering	DAP	17	1.5	5.6	37 -55	47
Physiological Maturity	DAP	17	6.5	14.6	103 -161	132
Samunt26						
50% Flowering	DAP	17	1.8	8.7	26 -58	46
Physiological Maturity	DAP	17	6.4	9.5	105 -158	132

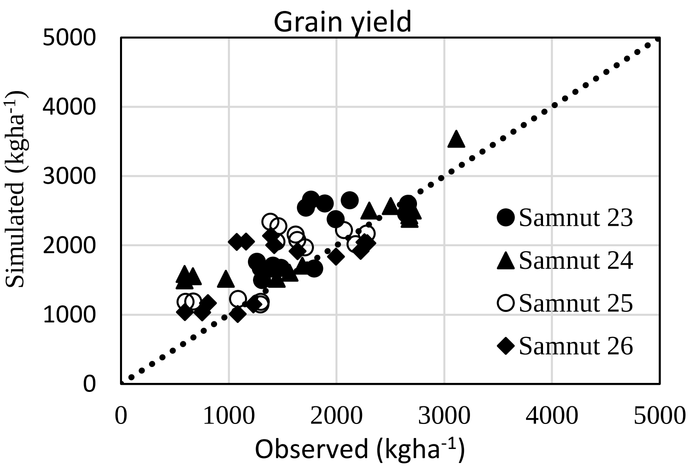


Fig. 4.4a –Model simulated vs. observed grain yield of groundnut using experiments conducted under different planting in 2015 and 2017 over Sudan savannah agroecologicall zones. *Samnut23(MBE= 343 kgha^{-1}, RMSE = 472 kgha^{-1}, RMSE$_n$ =26.6%, R^2 =0.55); Samnut24 (MBE= 266 kgha^{-1}, RMSE = 494 kgha^{-1}, RMSE$_n$ =27.9 %, R^2 =0.80); Samnut25 (MBE= 321 kgha^{-1};RMSE = 481 kgha^{-1}, RMSE$_n$ =32.5%, R^2 =0.51); Samnut26 (MBE= 249 kgha^{-1};RMSE = 491 kgha^{-1}, RMSE$_n$ =34.5%, R^2 =0.44); Number of observation per cultivar = 14.*

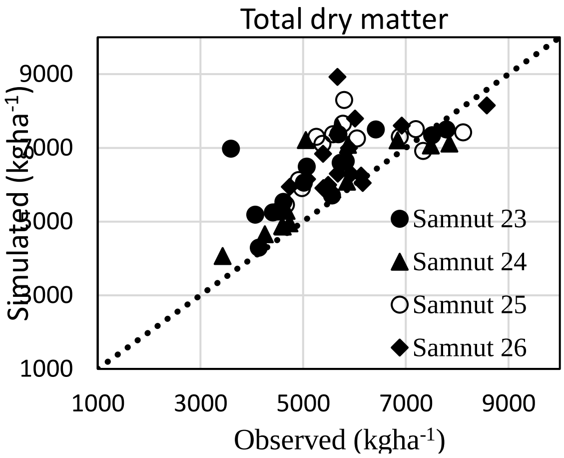


Fig. 4.4b –Model simulated vs. Observed total dry matter (TDM) of groundnut using experiment conducted under different planting in 2015 and 2017 over Sudan savannah agro-ecological zones. *Samnut23 (MBE= 932 kgha^{-1}, RMSE = 1282 kgha^{-1}, RMSE$_n$ =23.8 %, R^2 =0.47); Samnut24 (MBE= 533 kgha^{-1}, RMSE = 921 kgha^{-1}, RMSE$_n$ =16.9 %, R^2 =0.64); Samnut25 (MBE= 1063 kgha^{-1};RMSE = 1368 kgha^{-1}, RMSE$_n$ =23.2%, R^2 =0.34); Samnut26 (MBE= 870 kgha^{-1};RMSE = 1240 kgha^{-1},RMSE$_n$ =20.9%, R^2 =0.28); Number of observation per cultivar = 14.*

4.4.2.2. *Groundnut - Model performance for Seasonal analysis*

Results of seasonal analysis for mean simulated grain yield of cultivars at varying planting window (PW1- PW5) and locations by APSIM model over 26-year period (1985-2010) are presented in Table 8 and 9 for Adamawa and Borno States. The planting window and sites had influenced on grain yield for all the four (4) cultivars simulated under water-limited environment. Across the sites, the mean simulated grain yield decreases significantly from PW1 to PW5. The simulated PW suggests that the groundnut cultivars can be cultivated within the 75 days of planting window (PW1 and PW5) in the selected area but the grain yield will decline with delay PW. Also, the analysis suggests farmers can grow all the cultivars with the exception of Samnut

24 in Adamawa State during low rainfall year or when the onset of rain is delayed. The mean simulated yield indicates the farmers would attain optimum rain-fed yield for all cultivars when planted between early June and early July across the selected sites. Among the cultivars, Samnut 23 simulated highest mean yield across the PW followed by Samnut 25 and 26 while Samnut 24 in both States simulated the lowest yield.

As depicted in Table 8 (Adamawa State), the adapted cultivar based on the mean grain yield (*~1000 kg ha^{-1} threshold*) found all the cultivars (except Samnut24) suitable for cultivation in most sites simulated. The coefficient of variation (CV) was generally moderate across the sites between PW1 and PW5 with Samnut 23 ranging from 11.3 to 13.3%, Samnut24 12.5 – 15.5%, Samnut 25 11.3 – 13.6%, and Samnut26 10.7 to 12.6% respectively. Similarly, in Table 9 (Borno State), the simulation (based on ~1000 kg ha^{-1} grain yield threshold) revealed that all the cultivars are found suitable for all the sites simulated except for Samnut 24 in some few sites. The coefficient of variation (CV) was significantly lower across the sites for planting between PW1 and PW5. The CV for Samnut23 ranged from 9.4 to 11.8%, 10.6 – 13.7% for Samnut24, and 9.7 – 12.2% for Samnut25 and 8.9 to 11.1% for Samnut26.

Based on the simulated outputs, the four (4) groundnut cultivars simulated are adapted to the region and therefore, recommend for dissemination in both States except for sites/LGAs simulated below 1000 kgha^{-1} in Adamawa State and Borno State. However, farmers should be guided to adopt early planting window, alongside with developed good agronomic practices as well as recommended fertilizer inputs for higher productivity.

Table 4.8 Simulated grain yield (kgha^{-1}) of groundnut cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Adamawa State, Northeast Nigeria.

LGA	Site	PW1	PW2	PW3	PW4	PW5	Mean	DM	PW1	PW2	PW3	PW4	PW5	Mean	DM
		Samnut23							Samnut24						
Demsa	Mbula Kuli	1549	1617	1566	1500	1397	**1526**	**192**	1005	1035	1000	980	946	**993**	**132**
Girei	Wuroahi	1500	1540	1485	1405	1323	**1451**	**180**	995	1007	971	938	891	**960**	**125**
Girei	Daneyel	1536	1491	1423	1368	1211	**1406**	**227**	982	928	891	882	818	**900**	**157**
Yola North	Yelwa -Jambore	1587	1594	1496	1428	1217	**1464**	**237**	1031	1017	960	947	846	**960**	**146**
Gombi	Guyaku	1797	1790	1624	1436	1207	**1571**	**309**	1210	1200	1134	1016	890	**1090**	**187**
Gombi	Tawa	1812	1758	1686	1668	1609	**1707**	**210**	1164	1114	1058	1054	1059	**1090**	**151**
Guyuk	Chikila	1444	1355	1279	1246	1216	**1308**	**178**	944	872	831	811	795	**851**	**134**
Guyuk	Lakumna	1491	1438	1384	1361	1364	**1407**	**196**	962	901	866	856	871	**891**	**149**
Hong	Dulmava	2037	2035	1942	1829	1541	**1877**	**271**	1336	1317	1269	1230	1101	**1251**	**168**
Hong	Hushere Zum	1783	1743	1655	1592	1461	**1647**	**224**	1147	1105	1054	1029	994	**1066**	**149**
Yola South	Fufore	1213	1336	1339	1301	1298	**1298**	**182**	833	937	946	917	884	**903**	**131**
Numan	Bare	1454	1524	1427	1336	1186	**1385**	**205**	947	986	931	893	831	**918**	**128**
Numan	Kodomti	1531	1486	1462	1462	1513	**1491**	**219**	973	915	901	900	929	**923**	**161**
Song	Suktu	1538	1567	1500	1433	1334	**1474**	**178**	1016	1014	976	955	903	**973**	**124**
Shelleng	Lakati_Libbo	1605	1620	1530	1441	1292	**1498**	**211**	1038	1027	984	948	894	**978**	**135**
Shellenge	Jonkolo - Lama	1314	1352	1336	1299	1255	**1311**	**167**	858	870	849	835	832	**849**	**132**
Song	Sabon Gari	1728	1689	1633	1625	1610	**1657**	**193**	1113	1060	1014	1012	1037	**1047**	**146**
Demsa	Demsa-Nassarawo	1497	1470	1408	1389	1332	**1419**	**199**	968	925	884	881	871	**906**	**148**
Mean		**1579**	**1578**	**1510**	**1451**	**1354**			**1029**	**1013**	**973**	**949**	**911**		
Deviation from mean		**199**	**179**	**184**	**192**	**177**			**137**	**125**	**140**	**147**	**132**		
Coefficient of variation (%)		**12.6**	**11.3**	**12.2**	**13.3**	**13.1**			**13.3**	**12.3**	**14.4**	**15.5**	**14.5**		
		Samnut25							Samnut26						
Demsa	Mbula Kuli	1236	1290	1256	1209	1133	**1225**	**152**	1223	1275	1226	1167	1074	**1193**	**146**
Girei	Wuroahi	1201	1234	1194	1140	1073	**1169**	**142**	1174	1206	1154	1089	1021	**1129**	**141**
Girei	Daneyel	1228	1181	1139	1102	989	**1128**	**182**	1225	1189	1131	1073	939	**1111**	**175**
Yola North	Yelwa -Jambore	1270	1270	1200	1160	1004	**1181**	**185**	1251	1249	1172	1107	926	**1141**	**191**
Gombi	Guyaku	1452	1444	1336	1179	1002	**1283**	**241**	1390	1383	1247	1094	916	**1206**	**242**
Gombi	Tawa	1450	1400	1346	1333	1304	**1367**	**171**	1425	1393	1338	1316	1242	**1343**	**159**
Guyuk	Chikila	1155	1084	1032	1003	981	**1051**	**145**	1131	1063	1002	975	947	**1024**	**134**
Guyuk	Lakumna	1187	1139	1104	1088	1093	**1122**	**160**	1177	1143	1102	1077	1074	**1115**	**144**
Hong	Dulmava	1632	1623	1562	1490	1270	**1516**	**209**	1597	1589	1515	1406	1168	**1455**	**214**
Hong	Hushere Zum	1428	1390	1328	1277	1192	**1323**	**178**	1401	1375	1305	1243	1124	**1289**	**175**
Yola South	Fufore	982	1094	1097	1064	1052	**1058**	**150**	942	1025	1026	999	990	**997**	**137**

Numan	Bare	1164	1216	1138	1083	975	**1115**	**156**	1150	1197	1106	1031	904	**1077**	**161**
Numan	Kodomti	1223	1174	1161	1155	1204	**1183**	**181**	1219	1192	1172	1178	1202	**1193**	**160**
Song	Suktu	1233	1250	1207	1164	1081	**1187**	**141**	1200	1226	1166	1111	1026	**1146**	**137**
Shelleng	Lakati_Libbo	1281	1288	1227	1164	1060	**1204**	**162**	1265	1278	1195	1118	987	**1169**	**167**
Shellenge	Jonkolo - Lama	1050	1083	1073	1047	1019	**1054**	**140**	1034	1065	1053	1019	974	**1029**	**123**
Song	Sabon Gari	1383	1338	1289	1286	1290	**1317**	**160**	1355	1339	1292	1282	1258	**1305**	**141**
Demsa	Demsa-Nassarawo	1199	1165	1126	1112	1078	**1136**	**162**	1183	1167	1116	1097	1036	**1120**	**150**
Mean		**1264**	**1259**	**1212**	**1170**	**1100**			**1241**	**1242**	**1184**	**1132**	**1045**		
Deviation from mean		**162**	**142**	**153**	**159**	**143**			**147**	**133**	**136**	**141**	**131**		
Coefficient of variation (%)		**12.8**	**11.3**	**12.6**	**13.6**	**13**			**11.9**	**10.7**	**11.5**	**12.4**	**12.6**		

DM: *Deviation from mean;* ***PW1-*** *Planting window 1 (15th -31st May);* ***PW2-*** *Planting window 2 (1st -15th June);* ***PW3-*** *Planting window 3(16th -30th June);* ***PW4-*** *Planting window 4 (1st -15th July);* ***PW5-*** *Planting window 5 (16th -31st July).*

Table 4.9 Simulated grain yield ($kgha^{-1}$) of groundnut cultivars at varying planting window (PW) between 1985 and 2010 in selected LGA and sites in Borno State, Northeast Nigeria.

LGA	Site	PW1	PW2	PW3	PW4	PW5	Mean	DM	PW1	PW2	PW3	PW4	PW5	Mean	DM
					Samnut23							**Samnut24**			
Bayo	Balbaya	1890	1917	1836	1724	1548	1783	229	1243	1238	1180	1138	1065	1173	154
Bayo	Briyel	1847	1813	1742	1705	1731	1767	166	1242	1208	1146	1119	1107	1164	138
Bayo	Jara-Dali	1141	1197	1199	1186	1218	1188	123	806	859	853	837	830	837	92
Biu	Buratai	1696	1626	1477	1304	1131	1447	263	1107	1071	993	905	783	972	169
Biu	Kabura	1977	1935	1828	1691	1505	1787	241	1294	1244	1186	1136	1042	1181	154
Biu	Mathau	1990	1934	1812	1697	1593	1805	227	1310	1254	1185	1105	1102	1191	155
Biu	Tum	1295	1305	1262	1211	1179	1251	134	904	917	882	841	800	869	102
Hawul	Kwajaffa	1762	1723	1594	1499	1429	1601	203	1183	1156	1081	1020	983	1085	140
Hawul	Puba Vidau	1772	1698	1477	1346	1201	1499	261	1276	1221	1077	988	897	1092	185
Hawul	Sakwa Hema	1968	1936	1824	1679	1451	1772	265	1282	1238	1185	1145	1022	1175	161
Kwaya-Kusar	Bila Gusi	1496	1443	1392	1362	1276	1394	211	952	892	860	852	845	880	151
Kwaya-Kusar	Kurbo Gayi	1989	1949	1892	1844	1782	1891	210	1307	1248	1190	1177	1174	1219	160
Shani	Gwaskara	2002	1954	1892	1888	1855	1918	194	1308	1243	1198	1193	1220	1233	150
Shani	Kubo	1504	1459	1411	1413	1419	1441	211	958	898	864	861	892	895	156
Shani	Lakundum	2005	1954	1898	1889	1884	1926	198	1302	1244	1201	1191	1223	1232	152
Mean		**1756**	**1723**	**1636**	**1563**	**1480**			**1165**	**1129**	**1072**	**1034**	**999**		
Deviation from mean		**173**	**163**	**180**	**184**	**165**			**133**	**119**	**131**	**142**	**129**		
Coefficient of variation (%)		**9.9**	**9.4**	**11**	**11.8**	**11.2**			**11.4**	**10.6**	**12.2**	**13.7**	**12.9**		
				Samnut25							**Samnut26**				
Bayo	Balbaya	1514	1530	1470	1397	1266	**1435**	**181**	1482	1504	1425	1329	1180	**1384**	**180**
Bayo	Briyel	1492	1461	1403	1373	1383	**1423**	**144**	1433	1407	1348	1322	1346	**1371**	**123**
Bayo	Jara-Dali	931	981	984	970	991	**971**	**103**	873	916	914	911	935	**910**	**94**
Biu	Buratai	1374	1316	1202	1068	921	**1176**	**213**	1330	1270	1146	1002	870	**1124**	**208**
Biu	Kabura	1584	1550	1474	1382	1227	**1443**	**191**	1550	1520	1426	1307	1159	**1393**	**190**
Biu	Mathau	1605	1553	1457	1362	1313	**1458**	**180**	1557	1513	1408	1317	1220	**1403**	**178**
Biu	Tum	1058	1067	1032	988	961	**1021**	**113**	994	1002	965	928	906	**959**	**100**

Hawul	Kwajaffa	1426	1397	1296	1214	1171	**1301**	**165**	1364	1329	1223	1159	1095	**1234**	**154**
Hawul	Puba Vidau	1481	1421	1242	1133	1021	**1259**	**215**	1356	1296	1129	1029	922	**1146**	**198**
Hawul	Sakwa Hema	1581	1549	1466	1382	1189	**1433**	**208**	1538	1514	1419	1289	1118	**1376**	**207**
Kwaya-Kusar	Bila Gusi	1187	1144	1108	1095	1038	**1115**	**168**	1192	1155	1112	1079	987	**1105**	**160**
Kwaya-Kusar	Kurbo Gayi	1596	1552	1502	1479	1440	**1514**	**172**	1556	1533	1484	1437	1373	**1477**	**158**
Shani	Gwaskara	1607	1560	1503	1509	1502	**1536**	**163**	1570	1533	1496	1482	1428	**1502**	**143**
Shani	Kubo	1195	1153	1116	1122	1136	**1145**	**172**	1202	1171	1138	1136	1118	**1153**	**155**
Shani	Lakundum	1608	1560	1506	1504	1520	**1540**	**165**	1571	1535	1497	1488	1459	**1510**	**146**
Mean		**1416**	**1386**	**1318**	**1265**	**1205**			**1371**	**1347**	**1275**	**1214**	**1141**		
Deviation from mean		**145**	**135**	**149**	**155**	**138**			**127**	**120**	**132**	**135**	**123**		
Coefficient of variation (%)		**10.2**	**9.7**	**11.3**	**12.2**	**11.5**			**9.2**	**8.9**	**10.4**	**11.1**	**10.8**		

DM: *Deviation from mean;* ***PW1-*** *Planting window 1 (15th -31st May);* ***PW2-*** *Planting window 2 (1st -15th June);* ***PW3-*** *Planting window 3(16th -30th June);* ***PW4-*** *Planting window 4 (1st -15th July);* ***PW5-*** *Planting window 5 (16th -31st July).*

4.5. Conclusions

Our results show that APSIM for sorghum and pearl millet and groundnut can accurately predict the performance of crop varieties in northern Nigeria. The model simulated higher potential grain for pearl millet than sorghum suggesting that the region is more suitable for pearl millet than sorghum crop. The soil and weather conditions at both States are variable. The simulated potential grain yield was higher for all the crops (sorghum, pearl millet, and groundnut in Borno than in Adamawa. These results may be associated with higher rainfall across the selected sites in the Borno States and better soil fertility status. In both States, ICSV400, Improved Deko, CSR01, and Samsorg44 are recommended for dissemination for most sites and planted within 45 days planting window (PW1 and PW3) for higher productivity. Also, dissemination of SK5912 (late cultivar) should adopt only early planting (PW1&PW2) for better productivity. All the three pearl millet cultivars tested are adapted for cultivation for dissemination, and farmers should be guided to adopt planting window (PW2 & PW3) alongside with the recommended fertilizer inputs for higher productivity. Similarly, all the four (4) groundnut cultivars simulated are therefore recommended for dissemination. Also, farmers should be guided to adopt early planting window (within the first 60days), good agronomic practices as well as recommended fertilizer inputs for higher productivity.

References

Ajeigbe, H.A., F. M. Akinseye, A. Kunihya, A.I. Abdullahi and A.Y., 2019. Response of pearl millet (*Pennisetum glaucum* L.) to plant population in the semi-arid environments of Nigeria. Net *Journal of Agricultural Science* Vol. 7(1), pp. 13-22, DOI: 10.30918/NJAS.71.18.036.

Ajeigbe, H.A., F.M. Akinseye, A. Kunihya and J. Jonah 2018a. Productivity and Water Use Efficiency of Sorghum [*Sorghum bicolor* (L.) Moench] Grown Under Different Nitrogen Applications in Sudan Savanna Zone, Nigeria. International Journal of Agronomy. https://doi.org/10.1155/2018/7676058.

Ajeigbe, H.A., F.M. Akinseye, A Kunihya and J. Jonah 2018b. Sorghum yield and water use under Phosphorus applications in Sudan Savanna zone of Nigeria. *Global Advanced Research Journal of Agricultural Science.* Vol 7(3): 245-257, ISSN: 2315-5094.

Ajeigbe, H.A., B.B. Singh, J.O. Adeosun, and I.E. Ezeaku, (2010b). Participatory on-farm evaluation of improved legume-cereals cropping systems for crop-livestock farmers: Maize-double cowpea in Northern Guinea Savanna Zone of Nigeria. *African Journal of Agricultural Research*, Vol. 5(16), pp. 2080-2088.

Akinseye, F.M, M. Adam, M.P. Hoffmann, P.C.S Traore, S.O Agele, and A.M. Whitbread 2017. Assessing crop model improvements through comparison of sorghum (sorghum bicolor L. Moench) simulation models: a case study for West African cultivars. *Field Crop Research,* Vol. 201:19-31.

Akinseye, F.M, H.A. Ajeigbe, P.C.S. Traore, S. O. Agele, B. Zemadim, Whitbread, A.M. (2020). Improving sorghum productivity under changing climatic conditions: a modelling approach. *Field Crop Research*, Vol. 246 (1). https://doi.org/10.1016/j.fcr.2019.107685.

Akinseye, F. M., H.A. Ajeigbe, M.I. Ahmed, P.C.S. Traore, R. Tabo, and Whitbread, A.M. (2020). Predicting sorghum performance from big on-farm data in the savannah zone of northern Nigeria. A paper proceeding of 2nd Int'l Crop Modelling Symposium - ICROPM 2020 tagged "Crop modelling for Agriculture and Food Security under Global Change", 3-5 February 2020, Montpellier, France: Pp 236-237.

Akinseye, F. M. H. A. Ajeigbe, I. Angarawai, R. Tabo, A. Kunihya, T. Abdulazeez, (2018). Exploring Niches of Medium-season grain sorghums in Dryland areas of Nigeria- Coping strategies with impacts of climate variability. Poster presented at Sorghum in the 21st century conference:9th -12th April 2018, held Century city conference centre, Cape Town, South Africa.

Akinyemi, A.I. (2014). "Demographic dynamics and development in Nigeria". *African Population Studies*. 27 (2): 239–248. doi:10.11564/27-2-471.

Carberry, P.S., Hammer, G.L., and Muchow, R.C. (1993a.) Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. III. Senescence and prediction of green leaf area. *Field Crops Research*, 33, 329–351.

Carberry, P.S., Muchow, R.C., and Hammer, G.L., (1993b.) Modelling genotypic and environmental control of leaf area dynamics in grain sorghum. II. Individual leaf level. *Field Crops Research*, 33, 311–328.

Dalgliesh, N., Z. Hochman, Huth, N. and Holzworth, D. (2016). Field protocol to APSoil characterizations. Version 4. Australia: CSIRO.

Dingkuhn, M., Soulié, J.C., Lafarge, T. (2011). Samara V2: A cereal crop model tostudy G x E x M interaction and phenotypic plasticity, and explore ideotypes. In: AgMIP Rice International Workshop, 28–30 August, Beijing, China.

Echekwu CA, Ntare BN, Alhassan U, Mohammed, S.G, Alabi O. (2012). Proposal for Registration and Release of ICIAR-19BT (SAMNUT 24) as a new Groundnut Variety in Nigeria

FAOSTAT (2018) http://www.fao.org/faostat/en/#data.

FAO (2017). Food and Agricultural Organization. (2017). Report- FAOSTAT Production Year 2011.

Funk, C., P. Peterson, M. Landsfeld, D. Pedreros, J. Verdin, S. Shukla, G. Husak, J. Rowland, L. Harrison, A. Hoell and J. Michaelsen (2015). "The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes". Scientific Data 2, 150066. doi:10.1038/sdata.2015.66

FMARD (2011). Federal Ministry of Agriculture and Rural Development, "Agricultural transformation agenda: we will grow Nigeria's agricultural sector," Draft for Discussion, Executive Summary Abuja, Nigeria, Federal Ministry of Agriculture and Rural Development, 2011.

Hammer, G.L., O. Erikvan, G. McLean, S. C. Chapman, I. Broad, P. Harland, and R.C. Muchow (2010). Adapting APSIM to model the physiology and genetics of complex adaptive traits in field crops. *Journal of Experimental Botany*, 61 (8), 2185–2202.

Holzworth, D.P., Huth, N.I., deVoil, P.G., Zurcher, E.J., Herrmann, N.I., McLean, G., et al., (2014). APSIM – evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software*, 62, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009.

Ibrahim U, Ayinde BT, Dauda H, Mukhtar AA, 2012. Socioeconomic factors affecting groundnut production in Sabon gari Local Government of Kaduna State, Nigeria. *International Journal of Food and Agric Economics*, 1(1):41-48.

Jamieson, P.D., Porter, J.R., Wilson, D.R., (1991). A test of the computer simulation model ARC-WHEAT on the wheat crop grown in Zealand. *Field Crops Research*, 27,337–350.

Jones, J.W., Hoogenboom, G., Porter, C.H., Boote, K.J., Batchelor, W.D., Hunt, L.A., Wilkens, P.W., Singh, U., Gijsman, A.J., and Ritchie, J.T. (2003). The DSSAT cropping system model. *European Journal of Agriculture*, 18, 235–265.

Mishra, A., J.W. Hansen, M. Dingkuhn, C. Baron, S.B. Traore, O. Ndiaye, and M.N. Ward. (2008). Sorghum yield prediction from seasonal rainfall forecasts in Burkina Faso. *Agricultural and Forest Meteorology* 148 (11): 1798–814. doi: 10.1016/j.agrformet.2008.06.007.

Mweu, B.M., T.E. Akuja and M.W. Mburu, (2016). Performance of six pearl millet (*Pennisetum glaucum* (L.) R. Br) varieties in the semi – arid Kitui County of Kenya. *International Journal of Agricultural Research and Review*: Vol. 4(3): pp 514-521, ISSN-2360-7971,

Mukhtar AA, 2009. Performance of three groundnut (*Arachis hypogaea* L.) varieties as affected by basin size and plant population at Kadawa. Ph.D. Dissertation Submitted to post graduate school, Ahmadu Bello University, Zaria. pp 173.

Singbo A., Sangare B., Vabi M.B., Affognon H., Ishaku Y. (2016). Analysis of Gross Margin for Groundnut Production under Groundnut Upscaling Project in Northern Nigeria.

Appendix

Recommended varieties based on decision support tools

Based on results from the simulations using DST, some market preferred varieties of the component crops were selected (Table 1). Though rice was not included in the simulation exercise, based on literature, experience among the farmers, seed companies and EA, three improved varieties of rice were recommended for the demonstrations and dissemination exercise in the activity area. Three improved varieties of maize, 5 improved varieties of sorghum and groundnut, 3 of millet, rice and cowpea, and 2 improved varieties of soybean together with improved agronomic technologies were deployed by the Activity.

Table 1. Recommended varieties using decision support tools (DST) to simulate the performance of Component crops in diverse agroecologies in Adamawa and Borno States

Crop	Varieties recommended Adamawa and Borno states	Remarks
Maize	IWD C2 SYN-W (SAMMAZ 15)	In both States, the maize varieties IWD C2 SYN-W (SAMMAZ 15) and 99EVDT STR-W (SAMMAZ 27) and 99EVDT STR-W (SAMMAZ 27) are recommended for production and dissemination. However, the yield produced by 99 EVDT is within the acceptable range for early maturing maize varieties in northern Nigeria and should be promoted alongside these varieties because of the uncertainty in the rainfall pattern.
	DTSTR SYN /IWD C3 SYN (SAMMAZ 51)	
	99EVDT STR-W (SAMMAZ 27)	
Sorghum	SAMSORG 40 (ICSV-400)	Based on the simulated potential yield outputs, we therefore, recommend only early and medium maturing cultivars such as ICSV400, Improved Deko, CSR01 and Samsorg44 respectively for dissemination for most sites in Adamawa and Borno States.
	ISAMSORG 45 (improved Deko)	
	CRS01	
	Samsorg44	
	SAMSORG 47)	
Millet	Jirani	Based on the simulated outputs, the three pearl millet cultivars tested are therefore recommended for dissemination, but Jirani is only recommended in Borno state.
	SOSAT C88	
	Super SOSAT	
Rice	FARO 44	Rice was not part of the study, but these three varieties are the best available according to several research results.
	FARO 52	
	FARO 61	

Cowpea	IT99K-573-1-1 (SAMPEA 14)	Because of the problem of the parasitic weed *S. gesneroides* in Borno State, only two Striga-resistant varieties (IT99K-573-1-1 and UAM 09 1051-1) are recommended for dissemination. In Adamawa, where *S. gesneroides* is not much of a problem, all the three varieties evaluated can be disseminated.
	IT99K-573-2-1 (SAMPEA 15)	
	UAM 1051-1 (FUAMPEA 2)	
Soybean	TGX 1904-6F	The model consistently simulated higher yields for two soybean varieties than those of the other varieties in all the sites in the two States. These varieties (TGX1951-3F and TGX1904-6F) are therefore recommended for dissemination in the two States.
	TGX 1951-3F	
Groundnut	SAMNUT 22	The analysis suggests farmers can grow all the cultivars/varieties in both states apart from SAMNUT22 which is not recommended in Adamawa State during low rainfall year or when the onset of rain is delayed.
	SAMNUT 23	
	SAMNUT 24	
	SAMNUT 25	
	SAMNUT 26	

Who we are

IITA is the lead research partner that generates agricultural innovations to meet Africa's most pressing challenges of hunger, malnutrition, poverty, and natural resource degradation. It is a member of the CGIAR System Office, a global research partnership that unites organizations engaged in research for sustainable development for a food secure future.