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SYSTEM DYNAMICS MODELLING OF MAIZE PRODUCTION UNDER FUTURE CLIMATE SCENARIOS IN KADUNA, NIGERIA

By

Udita Sanga, Laura Schmitt Olabisi, Saweda Liverpool-Tasie

Food Security Policy ***Research Papers***

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EXECUTIVE SUMMARY

Nigeria is the second largest producer of maize on the African continent with more than 5 million hectares of land under maize production and an annual area and yield growth rate of 4.1 % and 2.7% respectively (Beyene et al., 2016). However, maize yields in sub-Saharan African countries, including Nigeria, remain low compared with global averages. Yields may be further impacted by shifts in temperature and rainfall under climate change in the coming several decades, given that most maize in Nigeria is rainfed.

We used a system dynamics model combined with stakeholder input to simulate maize production in Kaduna state, Nigeria, under a range of scenarios including 1) adoption of hybrid early maturing maize varieties; 2) optimal fertilizer use; and 3) shifts in climate regimes. System dynamics modeling is a technique which allows researchers to investigate the future state of a complex system with both social and ecological components. Our goal with this model was not to replicate the accuracy of yield prediction generated by data-intensive agronomic models, but to build a tool for supporting policy decisions in the region while incorporating socio-ecological dynamics and stakeholder insights.

Overall, the model suggests that agricultural policies with respect to maize production should focus on developing and disseminating knowledge and accessibility of early maturing /drought tolerant maize varieties alongside efforts to promote more efficient integrated fertilizer management strategies (such as mixed organic and conventional fertilizers) which increase the agronomic use efficiency of EM hybrid maize varieties. However, even under these optimal efforts to improve maize production in the face of climate change, maize productivity is expected to first rise, and then decline by mid-century under expected precipitation and temperature shifts, demonstrating an inverted U-shaped curve.

In the context of a growing population, and therefore a growing demand for food, in Kaduna and in Nigeria more broadly, the results of this study imply the need for a diversification of the agricultural sector towards staple crops that will be less climate-sensitive than maize. This is consistent with other recent agronomic modeling work in sub-Saharan Africa which has found that climate change could severely impact staple food crop production, even under scenarios of technological advancement and fertilizer use (Ittersum et al. 2016; Sulser et al. 2014).

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INTRODUCTION

Maize production in Nigeria

Nigeria is the second largest producer of maize in the African continent with more than 5 million ha of land under maize production and an annual area and yield growth rate of 4.1 % and 2.7% respectively (Beyene et al., 2016). However, maize yields in sub-Saharan African countries, including Nigeria, remain low compared with global averages. Between 2011 and 2013, the average maize yield in Sub Saharan Africa was estimated at 1.8 Mg ha^{-1} compared with 2.8 Mg ha^{-1} in the Philippines, 3.1 Mg ha^{-1} in Mexico, and 4.4 Mg ha^{-1} in Thailand (Beyene et al., 2016).

Since the 1950's, breeders have attempted to address this yield gap with the development of improved varieties of maize which have been released in Nigeria. In the 1970's the International Institute for tropical Agriculture (IITA) in Ibadan, Nigeria started a maize improvement plan to develop Open Pollinated Varieties (OPVs) of maize (such as TZA, TZB, AND TZPB) whose yield was significantly higher than local varieties. In the early 1980's, IITA began to develop hybrid maize varieties (such as Oba super I and Oba Super II) and in the 1990's, hybrid maize varieties were released in the Nigerian seed market. Since the mid- 2000's the joint project between IITA and CIMMYT project on Drought Tolerant Maize Adoption (DTMA) in Nigeria has been developing various drought tolerant maize varieties which are available across Nigeria. According to DTMA project (Abate et al, 2017), the top five ranked cultivars are Oba Super9, Ba Hausa, EVDT99, 3DT Com and Yar Masara which cover nearly 23% of maize area in Nigeria. All except Yar Masara are drought tolerant.

According to Abate et. Al, (2017), the average number of cultivars grown in each household in Nigeria (3.363) is the highest among sub-Sahara African countries. Most farmers report local varieties as preferable for food consumption due to the taste and ease in pounding, while high-yielding varieties (HYV) and other improved varieties were effective for higher yield and stability in abiotic stress (Abate et al, 2017). Despite all of these gains in maize breeding, yield levels in Nigeria are much lower than their agroecological potential (Vanlauwe et al. 2014) and the yield response of maize to fertilizer is low (Sheahan and Barrett, 2017; Liverpool-Tasie et al., 2017). Lack of sufficient nutrient inputs, soil quality, pests and diseases and drought are some of the major abiotic and biotic factors limiting maize productivity in Nigeria (Shiferaw et al. 2011, Vanlauwe et al. 2014).

Climate Change and Maize Production

Nigerian agriculture is primarily rain fed and water availability plays an important role in estimating crop yields. Variability in rainfall, the onset and length of the rainy season, rainfall amount and number of rainy days all play a role in crop production and yield specifically in rain fed regions of West Africa (Omotosho et al 2000). The spatial distribution of rainfall amount across Nigeria shows a gradual decline from the South to the North across the various climatic zones. Oguntunde et al (2012) have observed reduced rainfall trends in Northern regions of Nigeria and increased rainfall intensity in the wet season (August and September) in the South since the 1970s. According to Yayock and Owonubi (1985), the variability of rainfall in Northern Nigeria, as measured by onset dates, length of rainy season, and number of rainy days, is very high. This observation is also confirmed by more recent studies by Ayasina and Ogunbo

(2009), Oguntunde et al (2011) and Buba et al (2017) who observe an increase in seasonal rainfall variability in Northern Guinea and Guinea Savanna region in Nigeria which is much higher than the rainfall variability patterns in Southern Nigeria. An analysis of the trends of rainfall variability from 1901-2000 by Oguntunde et al (2011) reveals a drying trend across Nigeria since the 1970s, with increased rainfall variability of between -3.46 and +0.76 mm yr -2. Over 90 years, the Gaussian normal distribution of rainfall in Nigerian climatic zones shows that annual rainfall ranges from 1400 to 2700 mm (Guinean zone), 950 to 1400 mm (Savanna zone) and 450 to 1050 mm (Sahelian zone) (Ogungbenro & Morakinyo, 2014).

Climate projections for the various climate zones in Nigeria according to the Intergovernmental Panel on Climate Change (2007) are as follows (Table 1). Temperatures are expected to increase across all climatic zones, and while conditions may be on average wetter, rainfall variability is projected to increase as described above.

Table 1. Climate projections for 5 ecological zones in Nigeria 1961–2100, based on data from IPCC (available at http://ipcc-ddc.cru.uea.ac.uk). **Bold**: present conditions. Projections are for the year 2100. nc: no change, nsc: no significant change

	Port Harcourt	Ilorin	Kaduna	Kano	Maiduguri
Geography					
Region	Forest	Southern Guinea	Northern Guinea	Sudan savannah	Sahel savannah
Köppen classification	Af	Aw	Aw	BS	BS
Surface of country (%)	**25**	**21**	**19**	**28**	**7**
Precipitation					
Present amount (mm)	1200–3000	1000–1250	1000–1250	600–1000	<600
Rainy season (mo)	9–12	8–9	6	4	3
Projected: Rainy season	Wetter	Wetter	Wetter and longer	Wetter and earlier	Wetter until 2069
Dry season	nsc	nsc	nc	nsc	nsc
Maximum temperature					
Present (°C)	28–34	30–38	30–38	28–40	28–40
Lowest	August	August	August	January	January
Highest	March	March	March	May	May
Projected (°C)	31–36	34–40	34–43	32–43	35–46
Minimum temperature					
Present (°C)	21–24	17–24	15–24	12–26	10–26
Lowest	January	January	January	January	January
Highest	April	April	April	May	May
Projected (°C)	21–27	20–30	18–30	19–30	19–30
Vapour pressure					
Present (hPa)	27–31	17–28	8–25	5–25	6–25
Lowest	January	January	January	January	January
Highest	April	May	July	August	August
Projected (hPa)	33–38	22–34	12–33	10–32	10–33

Kaduna State (Demographics and Agriculture)

Kaduna falls in the Savanna region of Nigeria, with rainfall for the period 1991-2005 ranging from 1100 and 1400 mm./year, the number of rainy days ranging from 80 -115 days, and a monthly rainfall range of 2 mm to 500 mm. The average rainfall is least in March- April and highest in July-August-September (JAS) (Omonijo et al, 2014). Omonijo et al (2014) analyzed the pattern of rainfall in Kaduna from 1991 to 2005 using rainfall data collected from the Nigerian Meteorological Agency and found that, of rainy months, the average monthly rainfall is highest in July and lowest in March with no rainfall in the months of November to February. The authors also reported no serious delays or a shift in onset of rains in Kaduna. However, other studies report a declining trend in average rainfall amount (Abaje et al , 2010,Abdusallam,

2015) due to a substantial decline in average monthly rainfall in the months of July, September and October which are critical for crop production (Abaje et al, 2010).

According to the Kaduna State Policy report (2017), the population for Kaduna state from the National Population commission is 6,113,503 (2006 census) and projected to be about 8,216,037 in 2016. According to Nigerian census records, Kaduna's annual growth rate was +6.79 %/year between 1971 -1981; +8.62 %/year between 1981 -1991; +2.59 %/year between 1991 –2006; and +1.4 %/year between 2006-2015.

It is estimated that about 75 % of the population in Kaduna is engaged in small and medium scale farming (Nigeria Ministry of Agriculture, 2016). About 60% of Kaduna State citizens are self-employed, 27% are employed by private enterprises, and 13% are engaged in the public sector. Agriculture and related activities provide employment for 50% of the citizens, while 15% of them are engaged in retail trades, and the manufacturing sector employs just 5% of the population. Another 5% are employed in hotels and restaurants, education or social and personal services (Kaduna State Development Plan, 2014-2018 report, Ministry of Economic Planning, 2013)

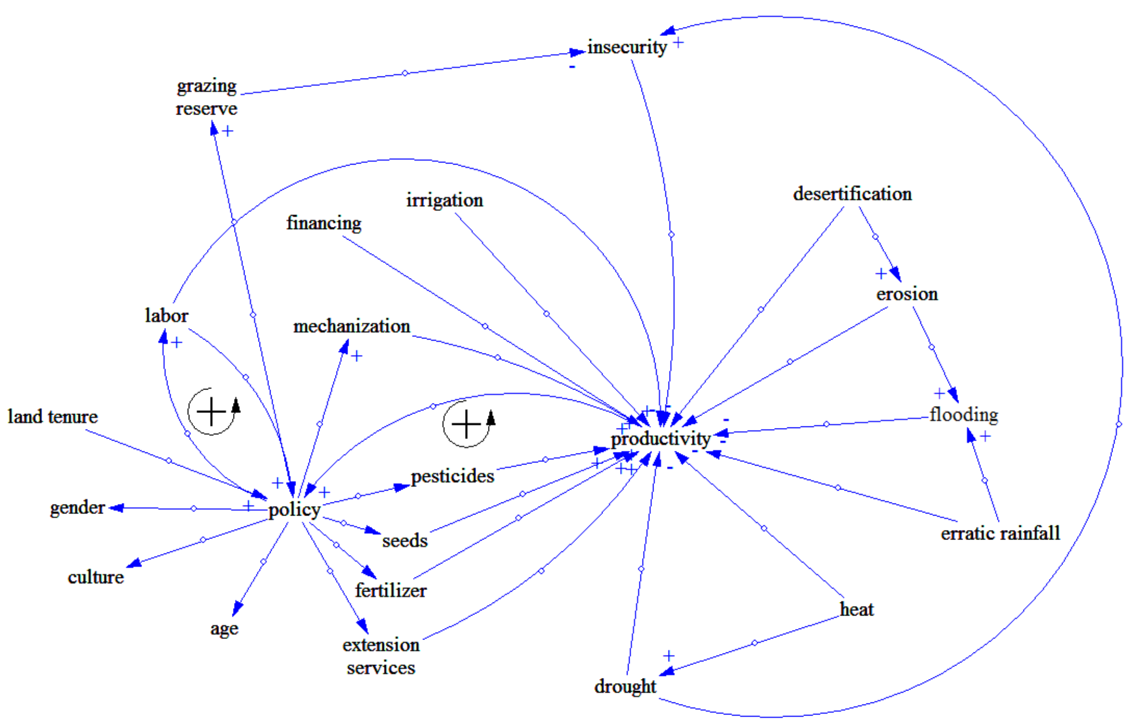


Figure 1. Causal Loop Diagram for North Central Nigeria, based on data collected in a participatory workshop in Ibadan Nigeria in June, 2016. See Schmitt Olabisi et al. 2016 for details.

SYSTEM DYNAMICS MODEL

System dynamics modeling is a technique which allows researchers to investigate the future state of a complex system with both social and ecological components. While highly detailed agronomic models have been used to forecast yields of staple crops in sub-Saharan Africa under a range of future climate conditions (Ittersum et al. 2016), these models have two major weaknesses. First, they are highly opaque to non-modelers, as the architecture of the models is not easily understandable without the ability to read computer code. Secondly, these models typically do not incorporate information about the socio-ecological context of the agricultural system which may influence yield. System dynamics models have been used in other fields such as climate modeling to build tools for supporting policy decisions that are simpler than the large-scale physically based global climate models, but retain the essential characteristics and behavior of the original models (Sterman et al. 2013). We took a similar approach here, incorporating essential dynamics from more data-intensive agronomic models into a more accessible system dynamics tool.

We developed the system dynamics model in this study with stakeholder input from Northern Nigeria, as described in detail in (Schmitt Olabisi et al. 2016). Based on the diagram developed by knowledgeable stakeholders, we parameterized the model using quantitative data as described below. First, we calibrated population, agriculture and maize production trends in Kaduna State from 1990 to 2017 (27 years). The BASELINE KD-MAIZE model simulates historical maize production in Kaduna while incorporating population growth, agricultural land use change, current adoption rates of existing maize technology (early maturing maize varieties, fertilizer use management) and past historical climate trends. By calibrating the model in this way, we ensured that the model was accurately representing the system dynamics that affect maize production in Kaduna.

The FUTURE KD-MAIZE model incorporates future climate trends in precipitation and temperature and maize production and explores various scenarios of climate, fertilizer use efficiency and better diffusion of drought tolerant maize varieties from 2017 to 2050.

Main elements of the baseline & future KD-MAIZE model

Detailed equations and parameters represented in the model may be found in Appendix 1. Below, we describe the operation of the variables in the model which follow from the stakeholder-designed model structure represented above.

Population Increase

The population of Kaduna in 1991 was 3,935,618. In the model, the population is initialized with the estimated population in 1990 which is ~ 3,500,000. The annual growth rate of population is calibrated at 3.2 % per year based on the Kaduna State Ministry of Agriculture report (2017). The percentage of population involved in agricultural activities is 75%. As population increases, the intensification of agricultural activities over time is represented in the model through the variable population_driven_intensification. The equation for population_driven_intensification is calibrated using temporal changes in population and agricultural land use in Kaduna.

Land Use

The total agricultural land area of Kaduna state is 2,020, 000 ha (Food Policy Report Kaduna 2016). In the model, land use dynamics are incorporated though initializing total land area at

4,105,126 ha. Land rate expansion is represented though a graphical function which shows a steady rise in rate of land expansion for agriculture. Data for land expansion rate was calibrated using data from a study done by Saleh (2014). Similarly, the proportion of land under maize cultivation was calibrated using historical maize production data from the study conducted by Ammani et al 2012. A graphical function was developed where proportion of land under maize varied from 0.06 as a proportion of agricultural land in 1990 to 0.19 in 2016, as maize land became a larger share of total agricultural land.

Maize production in Kaduna

Agro-climatology of maize is complex because of its phenological changes; maize is most susceptible to stress at flowering when silk growth, pollination, and kernel set occur (Shaw, 1977). Severe stress at flowering may lead to the complete abortion of ears, making the plant barren. Drought-affected ears typically have fewer kernels that will be poorly filled if drought extends throughout grain filling (Edmeades 2013). During the vegetative stage, maize needs abundant rainfall and during the flowering stage, it needs dry conditions (John and Olanrewaju 2014) Hence, weather in MAM (March April May) has a significant effect on maize yield in Nigeria for rain fed maize, which is sown at the onset of spring rains.

According to John and Olanrewaju (2014), maize yield is highly correlated with MAM rainfall, rainy days, and relative humidity, as well as T_{min} temperature. In JJA (June-July-August), rainfall amount, rainy days and T_{max} have a strong and negative correlation with maize yield, a weak positive correlation with relative humidity and a mild negative relationship with T_{min}. (John and Olanrewaju 2014). In JAS (July-August-September) season, there is a strong positive relationship between yield and rainfall, rainy days, maximum temperature and relative humidity but a strongly negative relationship with T_{min} (John and Olanrewaju 2014). Agronomic practices such as fertilizer use also influence maize yield (John and Olanrewaju 2014).

Climate parameters and maize yield

In the model, maize yield is estimated using a climate/yield model developed by John and Olanrewaju (2014) on maize yield and weather parameters in Ibadan, Southwest Nigeria using multilinear regression analysis from records of crop yield and weather variables from 2001 -2011.

The model is specified as follows:

$$
\begin{aligned}
yield_{maize} = \ & 3539.75 - 0.000151 * rainfall_{MAM} - 19.861 * Tmin_{MAM} + 4.234 \\
& * Rainydays_{MAM} - 6.7166 * RH_{MAM} - 0.422 * rainfall_{JJA} - 0.00004 \\
& * Tmax_{JJA} + 6.2573 * Rainydays_{JJA} - 0.7397 * rainfall_{JAS} - 55.4393 \\
& * Tmin_{JAS} + 35.1 * Tmax_{JAS} + 16.23581 * Rainydays_{JAS} - 13.46 * RH_{JAS}
\end{aligned}
$$

The climate variables were computed to correspond to three different phases of the maize growing season (MAM, JJA and JAS) where MAM (March April May) is the growing season, JJA (June July August) is the flowering and filling season, and JAS (July August September) is the harvesting season/ secondary planting season. RH is relative humidity; Tmax is the maximum temperature in the three-month period noted; and Tmin is the minimum temperature. The study found a significant relationship between crop yield, rainfall variability and temperature with the MAM season having the strongest influence on the annual crop yield (John and Olanrewaju, 2014).

The model is replicated for Kaduna state with an assumption that, while climatic regimes (and therefore the value of the climate parameters) differ across Nigeria, the climatic variables which impact yield are the same. According to Salako (2003), the soils of the two regions are similar, with course texture, a high proportion of sand, and low levels of organic matter and chemical fertility. However, the two regions differ based on other environmental characteristics such as the length of the growing period, which is 151-180 days for the northern Guinea savanna where Kaduna is located, versus 181-210 days for the southern Guinea savanna that includes Ibadan.

The calibration of climate parameters was done on the basis of a study by Omonijo et al (2014) on the monthly distribution of rainfall and rainy days, and their implications for crop production in Kaduna for the period 1991-2005 .

Early maturing Maize varieties

In the model, we assume that the majority of farmers in Kaduna used either traditional or high-yielding (non-early maturing) varieties of maize in the 1990s, and that the adoption of early maturing maize varieties took off in the early 2000s. This is consistent with historical trends in Nigeria as a whole, described above. Early maturing maize (EM) varieties were developed as a strategy to overcome variability in rainfall patterns and a shortening of the rainy season. They also offer flexibility in planting dates, which enables: (i) multiple plantings in a season to spread risk of losing a single crop to drought; (ii) late plantings in the case of delayed onset of rainfall; and (iii) avoidance of known terminal drought periods during the cropping season (CIMMYT, 2000). EM varieties are planted early at the onset of the rainy season (May-April) or in July/August, if spring rainfall is delayed. EM maize cultivars have favorable genes for high yield with a potential of increased yield of about 20-50% compared to other maize varieties. However, stakeholder consultations in Nigeria indicate that actual yields of EM varieties are lower than other improved varieties under 'normal' conditions. The EM varieties also **increased stability** across a broad range of water availability (Olaoye et al., 2009). We therefore conducted a sensitivity analysis on the EM yield advantage parameter in the model, varying this parameter between -25% and +50% of current maize, to observe its impact on total maize yield.

Adoption of Early Maturing maize varieties

Based on the theory of diffusion (Rogers, 1983): the adoption of EM maize varieties follows an exponential growth rate, given that the adoption of EM is still in its early stages and has not yet reached an inflection point.

FERTILIZER USE AND MAIZE YIELD POTENTIAL

The model also introduces the effect of fertilizer use on improving maize yield for both current and EM hybrid varieties. According to Ayinde et al. (2011), farmers in Kaduna used an average of 300 kg /ha of fertilizer with a maximum of 900 kg/ha and a minimum of 100 kg/ha on hybrid maize varieties. On OPV varieties, farmers applied on average of 100 kg of fertilizer (with maximum of 200 kg and minimum of 50 kg). Another study by Buba (2005), also suggests similar values; Liverpool-Tasie et al (2017) found that maize farmers in the main cereal producing area of the country (largely the north) used about 211 kg of fertilizer per hectare based on 2012 LSMS data. They also found that 67% of maize farmers used inorganic fertilizer (Liverpool-Tasie et al. 2017). However, fertilizer use alone was not sufficient to increase maize production in Nigeria; improvements in fertilizer use efficiency through integrated fertilizer management are also needed. According to Ibrahim et al (2014), who measured the technical efficiency of maize production in northern Nigeria, the average technical efficiency of maize farmers in Northern Guinea Savanna region (Kaduna) is 84% (this represents the ratio between the observed and potential output of a production unit). With more optimal input use, technical efficiency could be raised by 16% to achieve its maximum potential.

Hence, in the model, $Yield_{max}$ is calculated as :

$$Yield_{max}\ current = current\ maize\ yield / 0.84$$

$$Yield_{max}\ hybrid\ EM = hybrid\ EM\ yield / 0.84$$

Where 'current' yield represents the current mix of varieties in Kaduna, which include both high-yielding hybrid (non-EM) and OPV varieties. To understand the dynamics behind achieving maximum output from fertilizer use, the model calculates the extra grain that could be produced at a particular time step given the maize varieties.

$$extra\ grain\ EM\ hybrid = Yield_{max}\ EM\ hybrid - Hybrid\ EM\ yield$$

$$extra\ grain\ current = Yield_{max}\ current - current\ maize\ yield$$

Vanlauwe et al. (2014) conducted a meta-analysis of the impact of fertilizer management on the agronomic use efficiency (AE) of N fertilizer (defined as the extra grain yield per kg fertilizer N) in maize systems in Sub Saharan Africa. The study found the N-AE values of hybrid maize varieties is higher than local maize varieties (26 kg (kg N)-1 and 17 kg (kg N)-1 respectively. The use of fertilizers along with manure or compost further increases the N-AE values to 36 kg (kg N)-1.

EM hybrid AE and current_AE is initialized in the model as

$$EM\_Hybrid\_AE = if\ organic\_fertilizer\_use = 0\ then\ 26\ else\ 36$$

$$current\_AE = 17$$

Fertilizer required to achieve maximum grain potential is calculated as:

fert_required_EMhybrid = extra_grain_EMhybrid/EMHybrid_AE

fert_required_current = extra_grain_current/current_AE

Thereafter, the fertilizer amount applied to hybrid and current varieties are calculated as

current_fertilizer_amount = 100+fert_required_current

EM_hybrid_fertilizer_amount = 300+fert_required_EMhybrid

where the average amount of fertilizer used per ha for current maize varieties is 100 kg and for EM hybrid varieties is 300 kg (Ayinde et al. ,2011)

The model explores scenarios of improving agronomic fertilizer use efficiency for maize. According to Adediran and Banjoko (1995), the highest response of maize in savanna regions of Nigeria was to nitrogen rather than potassium or phosphorous, with an optimum application ranging from 50-100 kg N/ha. The model assumes N is the major limiting factor in increasing maize yield due to fertilizers.

Yield under fertilizer can be calculated using a Michaelis-Menten equation applied to maize yield and conventional + organic fertilizer use:

$$Yield_{fert} = \frac{Yield_{max} * fertilizeramt}{Km + fertilizeramt}$$

Where $Yield_{max}$ is the maximum yield achieved through fertilizer use and Km is a constant that represents the amount of fertilizer that would lead to production of $Yield_{max}/2$

In the model, we assume that the fertilizer amount of 100 kg/ha N leads to max yield in EM hybrid maize varieties; hence the value of Km is set to 50 kg/ha (for half of max yield). For current varieties, we assume that the fertilizer amount of 50 kg/ha N leads to max yield in current varieties, hence the value of Km is set to 25 kg/ha (for half of max yield).

MAIZE PRODUCTION IN KADUNA

In the model, the overall maize production in Kaduna is given by:

*KD_maize_production = ((EMV_adoption_rate*yield_fert_EMhybrid*land_under_maize) +(1-EMV_adoption_rate)*land_under_maize*Yield_fert_current)*

RESULTS

MODEL SIMULATION AND VALIDATION

PAST TRENDS (BASELINE KD MAIZE MODEL)

The BASELINE KD-MAIZE simulated the maize production in Kaduna state from 1990- 2005 for 10 model runs, with a different precipitation and temperature value selected for each run from a range of past temperatures, in order to simulate baseline production variability (Figure 2). The average value of the 10 model runs was compared with the actual values of maize production in Kaduna from 1990-2005. The correlation coefficient of the simulated values and actual values was 0.61 with actual maize production from 1990-2005 (Table 2).

Time Step	Year	Simulated Maize production in Kg (Average of 10 runs)	Actual Maize production, Metric tons	Actual Maize production in Kg
0	1990	311146451.54	426120.00	426120000
1	1991	349369353.60	529561.00	529561000
2	1992	301192773.20	563503.00	563503000
3	1993	426005257.51	484694.00	484694000
4	1994	510949166.13	751752.00	751752000
5	1995	545710399.18	670520.00	670520000
6	1996	507697785.48	462875.00	462875000
7	1997	590020216.17	953130.00	953130000
8	1998	568162739.77	1334343.00	1334343000
9	1999	595462426.39	1391048.00	1391048000
10	2000	603590168.96	812721.00	812721000
11	2001	610571642.93	832922.00	832922000
12	2002	580262471.80	826800.00	826800000
13	2003	573000168.37	944671.00	944671000
14	2004	639226498.02	635487.00	635487000
15	2005	573503373.35	907495.00	907495000

Table 2. Comparison of model-generated maize production and reported maize production from Kaduna State, 1990-2005.

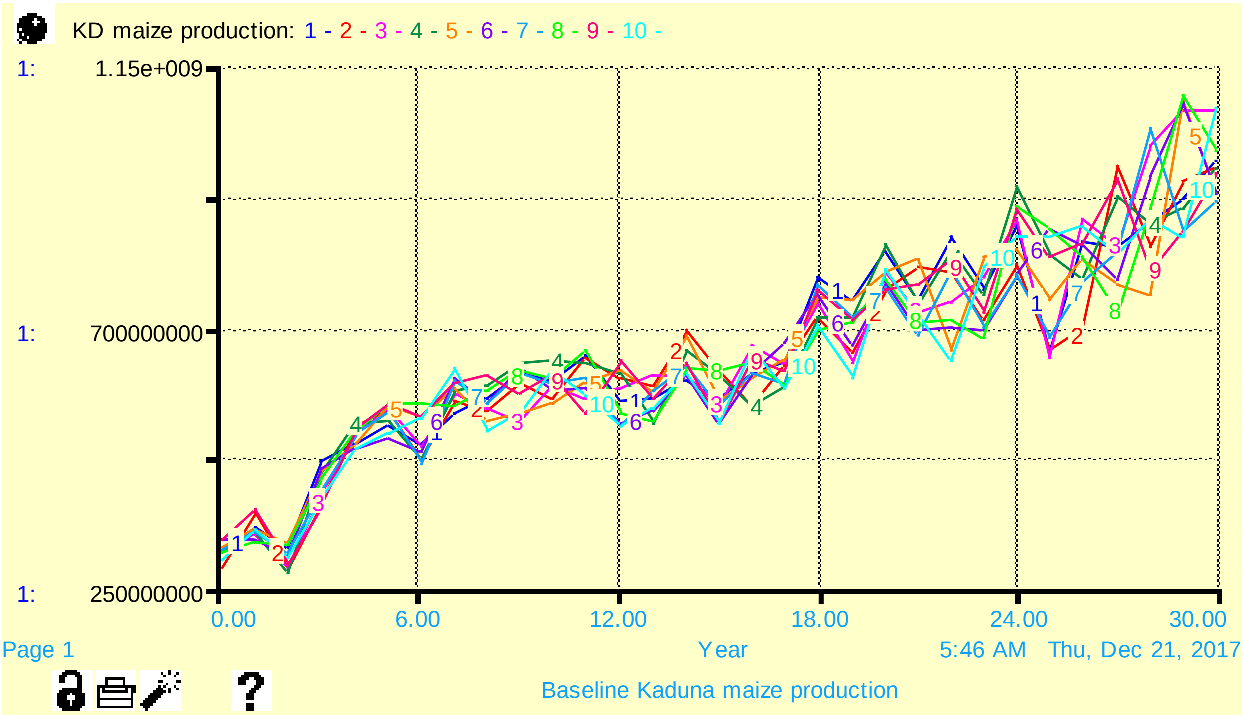


Fig 2: Simulated Maize production trends in Kaduna from 1990-2020

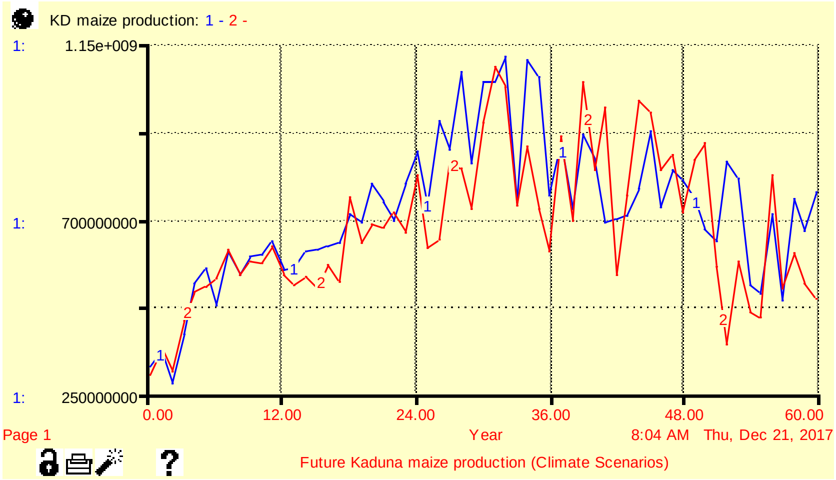
FUTURE TRENDS (FUTURE-KD MAIZE MODEL)

Climate projections for Kaduna (1961-2100 IPCC)

According to IPCC climate projections (2007), the West African Sahel is going to be wetter and hotter with an anticipated increase in temperature by 0.04-0.05 degree Celsius/year. Maximum temperatures are expected to increase from a current range of 30-38° C to 34-43° C, and minimum temperatures will increase from 15-24° C to 18-30°C. The model introduces these projections in the FUTURE_KD_MAIZE model through three additional variables. Tmax and Tmin projection variables increase the Tmax and Tmin values of MAM, JAS and JJA by 0.04 and 0.05 degrees per year. Rainfall projection is randomly selected between a minima and maxima which increases in both severity and intensity 10-40% across the model run. Severity is represented as rainfall amount in MAM, JAS and JJA, and intensity is represented as the number of rainy days.

In the FUTURE-KD-MAIZE model, the EMV adoption rate peaks at 99.4% at year 2030 under an assumption of 'maximum EMV adoption', and land expansion rate doubles by 2050 from 0.10% to 0.20%.

Simulation Results

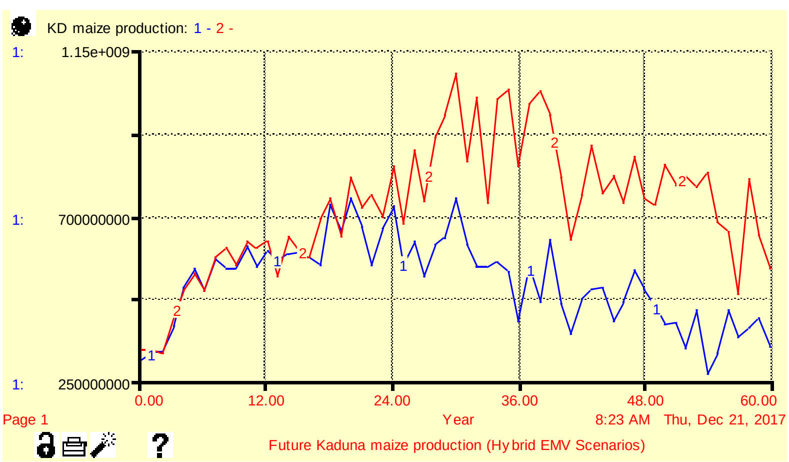


Trend line 1: maize production without climate change scenario

Trend line 2: maize production with climate change scenario

Figure 3: Maize production from 1990-2050 with and without climate change scenarios

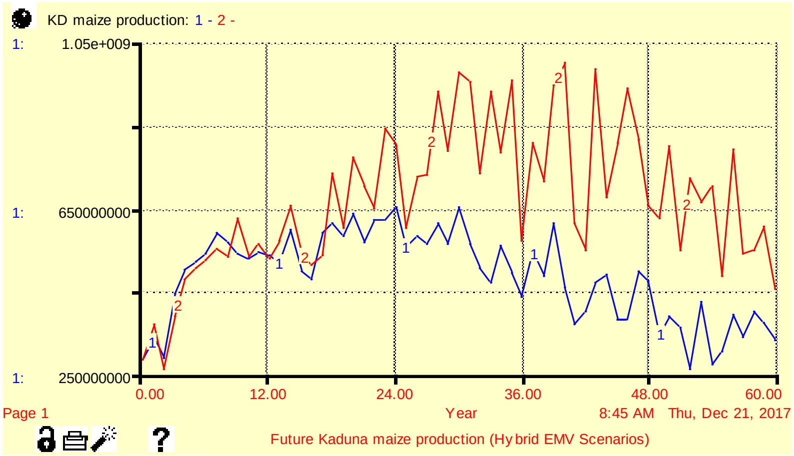
The simulation reveals that maize production will become highly variable and sensitive to weather fluctuations from the year 2025 onwards and gradually decline over time until mid-century (2050). The overall production of maize yield under climate change is slightly lower than the baseline maize production. Below, we test the influence of fertilizers and early maturing varieties on maize production under climate change.



a. Baseline scenario

Trendline 1: maize production ***without*** adoption of Hybrid Early maturing varieties

Trendline 2: maize production ***with*** adoption of Hybrid Early maturing varieties



b. Climate scenario

Trendline 1: maize production ***without*** adoption of Hybrid Early maturing varieties

Trendline 2: maize production ***with*** adoption of Hybrid Early maturing varieties

Figure 4: Maize production from 1990-2050 with and without adoption of EM varieties under baseline (a) and climate change (b) scenarios.

The simulation results reveal that in the absence of adoption of hybrid early maturing varieties, maize production declines significantly from 2020 onwards. In the presence of adoption of hybrid early maturing maize varieties, maize production increases (but is still sensitive to annual climate variability) until 2030 and then stagnates from 2030 to 2050. This occurs because in the model, the adoption of EM hybrid maize follows an S-shaped diffusion curve over time, where the adoption of EM hybrid maize is most rapid between 2000-2025. Past 2030, most farmers who are able and willing to adopt early maturing varieties have done so, so there are limited additional gains to this technology.

Consultations with stakeholders revealed that not all adopters of early maturing varieties experience yield gains. We therefore ran the model while varying the yield of early maturing maize varieties between -25% and +50% of open-pollinating varieties, under non-drought stressed conditions (Figure 5). Our conclusion from this exercise was that overall trends in maize production in Kaduna state are not highly sensitive to the relative yield advantage of early maturing varieties; however, the degree to which these varieties can mitigate climate variability is greater if the yield advantage of EM is greater.

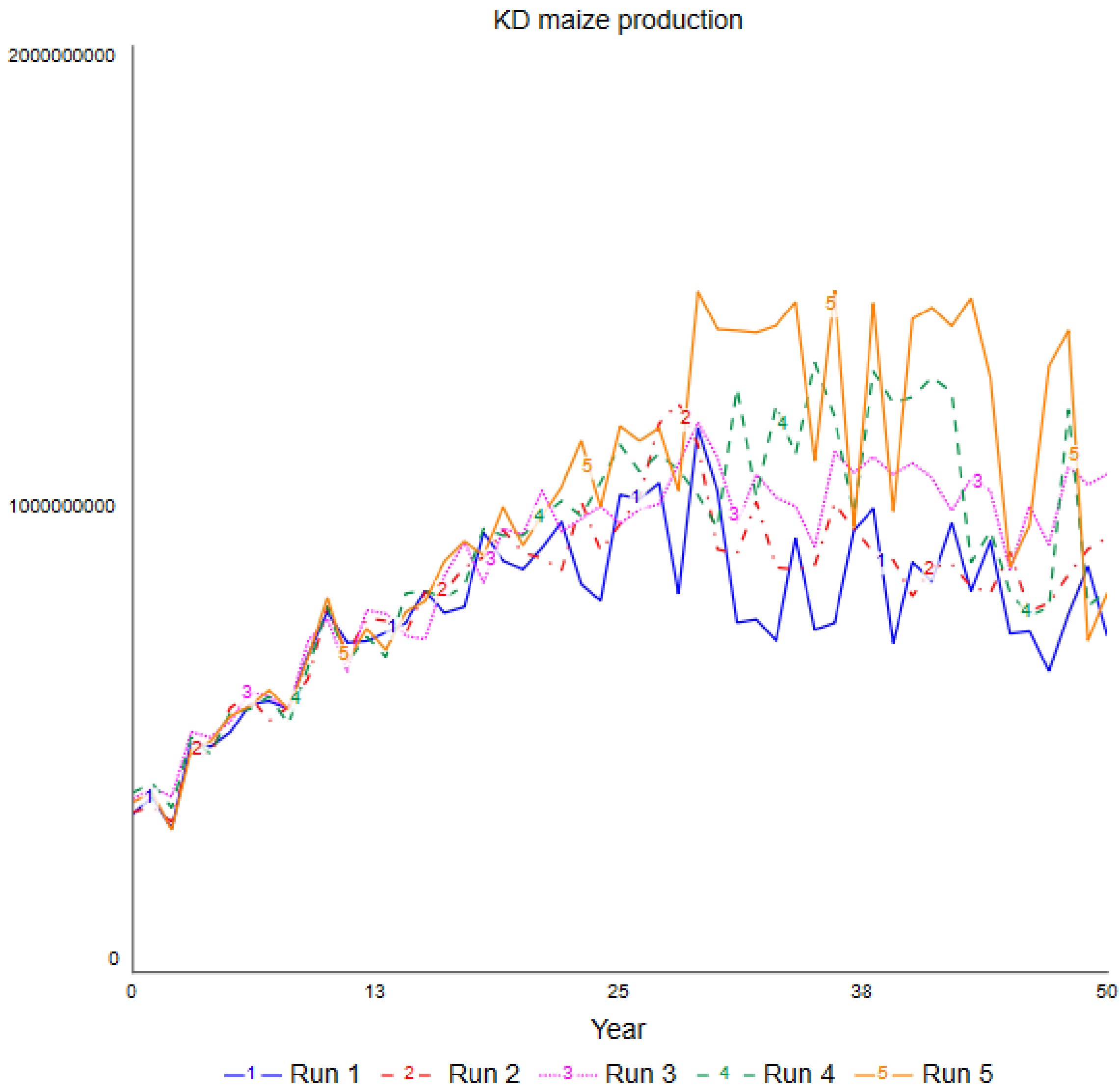
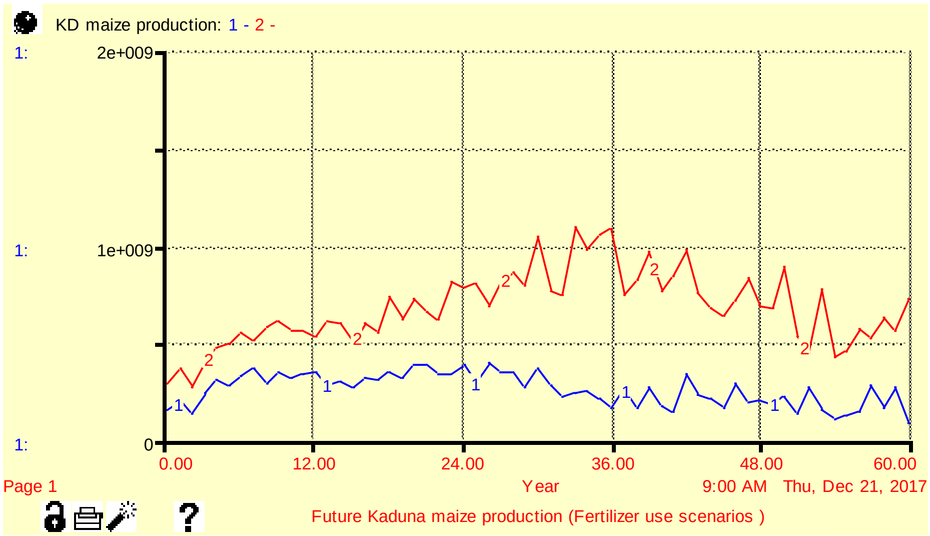


Figure 5: Sensitivity analysis of maize production in Kaduna to early maturing variety yield advantage when this parameter is 0.75 (Run 1), 0.9 (Run 2), 1.1 (Run 3), 1.3 (Run 4) and 1.5 (Run 5). For runs 1 & 2 where the yield of EM varieties is lower than current varieties, overall maize production shows a declining trend. For runs 4 &5 where yield of EM varieties is higher than current varieties, we notice a higher fluctuation in maize production over time, due to sensitivity of maize production to increased climate variability.

Fertilizer

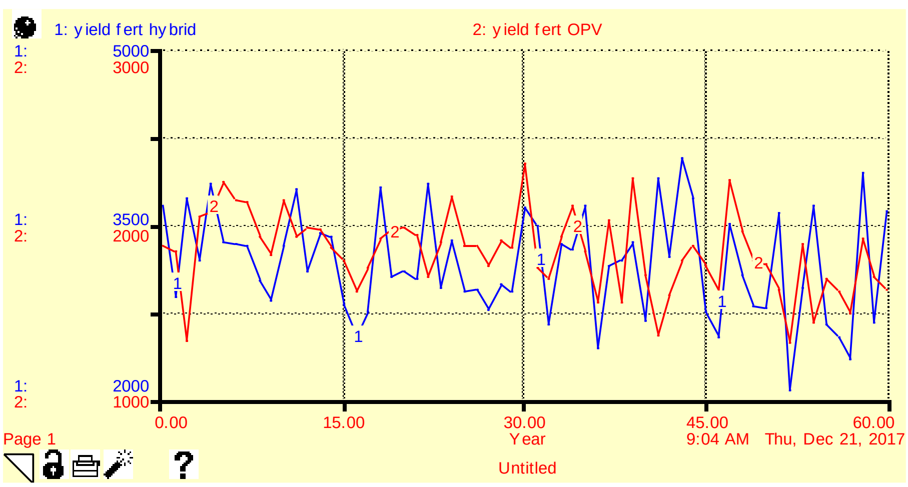
Maize production in Kaduna also responded strongly to fertilizer use (Figure 6). The advantages of fertilizer use were seen more strongly with the adoption of early-maturing varieties (Figure 7). Both organic and conventional fertilizers could deliver these productivity enhancements over time (Figure 8).



Trendline 1: maize production ***without*** fertilizer use

Trendline 2: maize production ***with*** fertilizer use

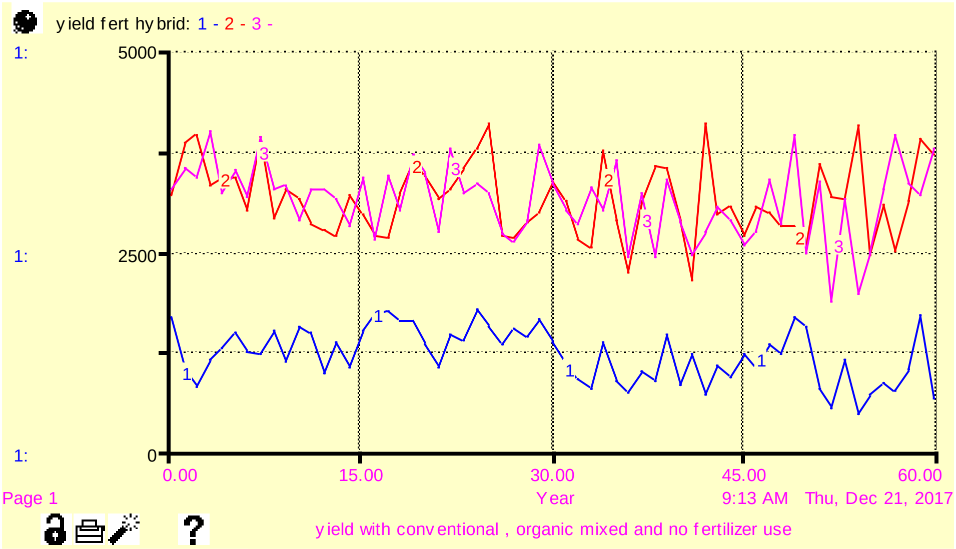
Figure 6. Maize production with fertilizer use is higher than production without fertilizer use.



Trendline 1: EM hybrid maize yield with fertilizer use

Trendline 2: current maize yield with fertilizer use

Figure 7. EM hybrid maize yield is higher (average around 3.5 tons per ha) with more efficient fertilizer use than current varieties (average around 2 tons per ha).



Trendline 1: EM hybrid maize yield with no fertilizer use

Trendline 2: EM hybrid maize yield with conventional fertilizer use

Trendline 3: EM hybrid maize yield with mixed conventional and organic fertilizer use

Figure 8. Maize Yield in Kaduna state under different fertilizer regimes.

CONCLUSIONS

Overall, the model suggests that agricultural policies with respect to maize production should focus on developing and disseminating knowledge and accessibility of early maturing /drought tolerant maize varieties alongside efforts to promote more efficient integrated fertilizer management strategies (such as mixed organic and conventional fertilizers) which increase the agronomic use efficiency of EM hybrid maize varieties. However, even under these optimal efforts to improve maize production in the fact of climate change, productivity is expected to first rise, and then decline by mid-century under expected precipitation and temperature shifts, demonstrating an inverted U-shaped curve.

This model did not explore the impact of late onset of spring rains on maize production, although this climatic pattern has not yet been recorded in Kaduna. Nor did the model investigate how a decrease in the number of rainy days and an increase in rainfall intensity could affect maize production. Future work could incorporate these additional climate signals.

In the context of a growing population, and therefore a growing demand for food, in Kaduna and in Nigeria more broadly, the results of this study imply the need for a diversification of the agricultural sector towards staple crops that will be less climate-sensitive than maize. This is consistent with other recent agronomic modeling work in sub-Saharan Africa which has found that climate change could severely impact staple food crop production, even under scenarios of technological advancement and fertilizer use (Ittersum et al. 2016; Sulser et al. 2014).

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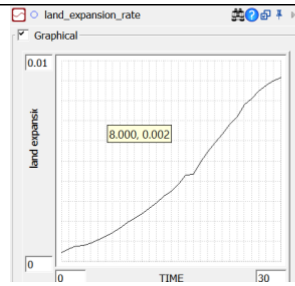
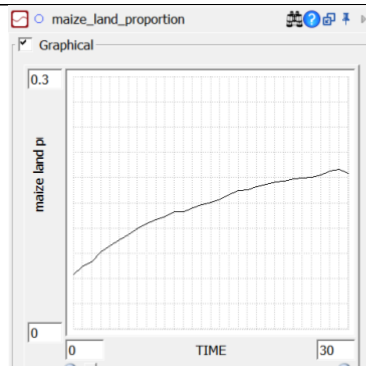
Appendix 1: Variables Represented in the Model

Variables	Initialization /calibration
INIT population	3,500,000
pop_growth_rate	3.2 %/year
Percentage pop in ag	0.8
pop_increase = population* (pop_growth_rate/100)	
ag_population = percentage_pop_in_ag*population	
population_driven_intensification = 1+ (TIME* (ag_population*0.003)/1000000)	
Total land	4105126
Land expansion rate (graphical function)	
Land expansion	Total_land*land_expansion_rate
Farm land proportion	0.568
Ag land	Total_land*(farm_land_proportion/population_driven_intensification)
Maize land proportion (Graphical function)	
Variables	**Initialization /calibration**
current maize yield = 3539.75-0.000151*rainfallMAM -19.861*TminMAM +4.234 *RainydaysMAM -6.7166 *rhMAM -0.422 *rainfallJJA -0.00004 *TmaxJJA -6.2573 *RainydaysJJA -0.7397 *rainfallJAS -55.4393 *TminJAS +35.1 *TmaxJAS +16.23581 *rainydaysJ_AS -13.46 *rhJAS	
rainfallMAM	random(50,250)
TminMAM	normal(25,5,12)

RainydaysMAM	random(8, 14)
rhMAM	random(20,35)
rainfallJJA	random(110,160, 12)
TmaxJJA	normal(35,5)
RainydaysJJA	random(40,50)
rainfallJAS	160
TminJAS	normal(20,5,12)
TmaxJAS	normal(30,5,12)
rainydaysJAS	30
rhJAS	random(50,75,12)