Renewable Agriculture and Food Systems

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Near-term impact of climate variability on yam rot incidence over a humid tropical region: projections in CORDEX-Africa scenarios

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Research Paper

Cite this article: Okoro UK, Akalazu JN, Nwulu NC (2021). Near-term impact of climate variability on yam rot incidence over a humid tropical region: projections in CORDEX-Africa scenarios. *Renewable Agriculture and Food Systems* **36**, 477–490. https://doi.org/10.1017/S1742170521000089

Received: 11 September 2020
Revised: 21 November 2020
Accepted: 11 February 2021
First published online: 5 April 2021

Key words:
Characteristic impact; rainfall variability; regional climate models; rot incidence; trend

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Abstract

The global population is projected to be enormous by the mid-21st century, whereas, most essential crops being sustained by the rain-fed agriculture are threatened by climate change. Therefore, the study investigated the projected near-future effect of rainfall variability on rot incidence and yam production in humid tropical Nigeria. Production data from the Food and Agriculture Organization and the Nigeria National Bureau of Statistics showed the significant increasing trend in the annual yam output. The field survey conducted in 2018 showed that the maximum percentage of rot incidence occurred in July. Climate Research Unit observational rainfall data from 1979 to 2018 showed the nonsignificant trend in the interannual rainfall variability; however, it showed low variability and a significant decreasing trend in the July rainfall. A pathogenicity test on yam samples confirmed rot by fungi, bacteria and nematodes as virulent pathogens, whereas, the nutritional qualities of the rotted yams were indicated. Monthly rainfall and rot incidence showed positive correlation ($r = 0.84$, significant at 99% from t-test). The positive characteristic impact values indicated that increase (decrease) in the monthly rainfall corresponds to increase (decrease) in the magnitude of monthly percentage rot incidence. Thus, the significantly decreasing rainfall reduced the quantity of rot incidence and consequently increased the annual yam production for the period. Selected CoOrdinated Regional Downscaling EXperiment-Africa models and the ensemble mean showed a good measure of agreement with observational rainfall in the historical experiments. The efficiencies of the bias-corrected outputs in the representative concentration pathway (RCP) 4.5 and 8.5 indicated improved 'reasonable' performances. Bias-corrected projections of the July rainfall showed an increasing trend in both the RCPs, which indicate a potential increase in rot incidence and the consequent decline in annual yam production. The findings are imperative in sustaining the global food supply.

Introduction

Yam plants belong to the genus *Dioscorea* in the plant family of *Dioscoreaceae* and are monocotyledonous (Etejere and Bhat, 1986; Okigbo, 2005). They are the second most important tuber crop globally after cassava in terms of production, and the third most important global source of carbohydrate after cereals and cassava (Wheatley *et al.*, 1995). They are predominantly cultivated as underground tubers in the tropics of West and East Africa, Asia, Central and South America, whereas, Nigeria, Côte d'Ivoire, Ghana, Benin and Togo accounts for 90% of the 36.6 million tons that are produced worldwide primarily by smallholder farmers (Sotomayor-Ramirez *et al.*, 2003; Katung *et al.*, 2006; IITA, 2013; Kolombia *et al.*, 2017; FAO, 2019). The yams occur in about 600 species with only seven of them being stapled food (Akoroda, 1993). The crop duration, from its planting to harvesting, ranges from 7 to 12 months (Ibeawuchi and Ofoh, 2003). Its economic importance has gone beyond being mostly a consumable staple food to the value chain in pharmaceutical and cosmetic industries thus becoming a major source of household income in the farming systems (IITA, 2013; Mignouna *et al.*, 2013; Nyadanu *et al.*, 2014; Bekele and Bekele, 2018). However, its traditional cultivation systems over West Africa has been under increasing pressure to adapt to the short fallow periods due to the scarcity of new lands for shifting cultivation, and to climate change (Manyong *et al.*, 1996).

Nigeria accounted for two-thirds of annual global yam production (Bergh *et al.*, 2019). It accounts for 80% of West Africa's production valued at about USD7.75 billion based on the 2.9 million hectares of land cultivated in 2012 (Ezulike *et al.*, 2006; Enesi *et al.*, 2018; NBS, 2019). The crop is commonly grown in the country's rain-forest and Guinea savanna zones, which have a higher amount of humidity and rainfall (Olasantan, 1999; Ike and Inoni, 2006; Bergh *et al.*, 2019). Depending on the species, size of the seed piece and environment, the crop's potential yield ranges from 20 to 50 tons per hectare, whereas, the labor cost from

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mounding to staking accounts for about 40% of the cultivation cost (Kader, 2005; Verte and Bečvařova, 2015). The tubers are mostly harvested between June and September and thereafter stored based on the cultural, traditional or technological capability of the people for consumption, sales and replanting (Amusa, 2000). A freshly harvested tuber contains about 70% water, 25% starch, 1–2% protein and traces of sugars, minerals and vitamins (Bassey and Akpan, 2015; Nweke, 2015). However, with the increasing population comes a higher demand of food and nutrition hence an increment in yam consumption, which makes the demand to exceed its supply (Shiwachi *et al*., 2008; Oluwatayo and Ojo, 2016).

An adequate storage system for the yams should prevent moisture loss, sprouting, attack by animals or insects and spoilage due to pathogens, thereby preventing reduction in weight and quality whereas retaining edibility and marketability (Osunde and Orhevba, 2009). In Nigeria, the yam barn is the main traditional storage method accepted by most farmers, whereas, improved yam storage technologies such as shelving has not been fully adopted (Okoedo-Okojie and Onemolease, 2009). The other storage methods are: the chemical preservation of the postharvest (Ogali *et al*., 1991; Ejechi and Ilondu, 1999), the no-chemical treatment of curing of yams in the sun immediately after harvest (Okigbo and Ikediugwu, 2002) and the cold room preservation of the postharvest below 10°C (Eze *et al*., 2015). However, the major constrain is that more than 50–60% of the harvests are lost during storage starting from the third month and peaking in the sixth month while the tubers lose up to 50% of their fresh matter (Eze *et al*., 2015). This constrain is not peculiar to Nigeria as studies have shown that more than 25% of global yam production is lost to storage annually (Nyadanu *et al*., 2014). Nigeria recorded its highest yam loss of over 3.7 million metric tons in 2006 (Verter and Bečvářová, 2015). The National Technical Committee on Nigeria Yam Export Programme has targeted USD10 billion earnings from the country's yam export by the year 2022 (Tribune, 2018). Indeed, the storage losses are attributed to microbial rot, with fungi having a superior effect compared to bacteria and nematodes (Otusanya and Jeger, 1996; Okoedo-Okojie and Onemolease, 2009; Nweke, 2015).

Studies have shown that rot severity is prevalent in the humid forest region of Nigeria (Dania *et al*., 2019). Based on their symptoms and causal agents, the rot is categorized into dry, wet and soft rot, respectively, and the dry rot is considered the most devastating (Amusa and Baiyewu, 1999; Amusa *et al*., 2003; Anjorin *et al*., 2014). The microorganisms infect the tubers through diseased foliage, roots or mother tubers, or during harvest and transportation to storage (Ogundana *et al*., 1970; Enesi *et al*., 2018). Several studies have investigated the pathogenicity of the rot, whereas, others suggested that biological/botanical methods to be used in preventing the rots owing to their advantage over chemical methods in harming both the tuber and the environment (Okigbo, 2005; Kumar *et al*., 2007). In some of the previous studies, the fungal organism *Trichoderma harzianum* has been effective at inhibiting the pathogenic effect of the fungal pathogenic rot caused by *Colletotrichum* species and *Penicillium purpurogenum* (Gwa and Abdulkadir, 2017; Gwa and Ekefan, 2017). The fungal pathogens *Aspergillus niger*, *Lasiodiplodia theobromae*, *Rhizoctonia solani*, *Penicillium oxalicum*, *Fusarium oxysporum* and *Sclerotium rolfsii* are adequately inhibited by *Bacillus subtilis* (Dania *et al*., 2016). The aqueous and ethanolic extracts of neem samples have effectively inhibited the pathogens *S. rolfsii* and *L. theobromae* (Ezeonu *et al*., 2018). Also, *Mimosa pudica* has been effective at controlling the fungal pathogens *A. niger* and *F. oxysporum* (Okigbo *et al*., 2017). Similarly, the bacteria pathogens *Erwinia carotovora*, *Pseudomonas aeruginosa*, *Serratia marcescens* and *Klebsiella oxytoca* were completely inhibited by selected plant extracts that were synergistically administered (Shiriki *et al*., 2017). The nematode pathogens *Meloidogyne incognita*, *Scutellonema bradys* and *Pratylenchus brachyurus* were effectively reduced by using vine propagation compared to the conventional sett method (Claudius-Cole *et al*., 2020). Nevertheless, varying climate conditions such as relative humidity, air temperature and rainfall are considered to increase the incidence and severity of these causative pathogens (Olabiyi *et al*., 2017).

Optimum rot occurs at air temperature between 26 and 30°C, whereas, a significant rot from all pathogens occur in the range of 20–30°C at a relative humidity above 80% (Ogundana *et al*., 1970). These reduce the phenolics, saponins and other natural antioxidants in the tuber against the pathogenic organisms (Buzby and Hyman, 2012). Hence, the virulent pathogens will not infect the tubers if the climatic conditions are not favorable (Velasquez *et al*., 2018). It is common knowledge that climate change affects the growing pattern of most crops, hence becoming a major challenge to the global food system (Rosenzweig *et al*., 2014; Bashir *et al*., 2018; Manners and van Etten, 2018). There have been efforts to quantify the effect of climate variability on crops while other studies have attempted investigating the potential impacts from future climate variability (Nwaobiala and Nottidge, 2015; Manners and van Etten, 2018; Chen *et al*., 2020). A number of the studies have emphasized on the impact of climate change on the growing areas for yam production as well as on the rate of production (Sonder *et al*., 2010; Srivastava *et al*., 2012; Angba *et al*., 2020; Fan *et al*., 2020). Indeed, climate affects all life stages of both the pathogens and the tuber; however, climate change could have a positive, negative or neutral impact on plant diseases (Olabiyi *et al*., 2017).

The available primary tools for deducing future climate change scenarios due to changes in greenhouse gases concentrations, aerosols and land-use change across the world are climate models. The regional climate models (RCMs) dynamically downscale the global climate models (GCMs). Their outputs are at high-resolutions (up to 50 km) relevant for vulnerability, impact and adaptation studies (Giorgi and Mearns, 1999; Nikiema *et al*., 2017). The CoOrdinated Regional Downscaling Experiment (CORDEX) is the first international program offering a common protocol for downscaling experiments (Giorgi and Gutowski, 2015). The performances of the RCM within the CORDEX-Africa experiments have been validated in numerous studies (Mounkaila *et al*., 2015; Diallo *et al*., 2016; Akinsanola and Ogunjobi, 2017; Okoro *et al*., 2020).

In this study, we analyze the near-term (up to the year 2050) effect of rainfall variability on yam production, considering the impacts from yam rot, within the humid tropical region of Nigeria. The specific objectives of this study are (i) to evaluate the recent trend in yam production in Nigeria, (ii) to investigate the statistical relationship between yam production, yam tuber rot disease and rainfall variability and (iii) to investigate the projections in yam production and rot disease to the year 2050 based on the CORDEX-Africa models output. Variability is more pronounced in the rainfall trends than in any other climate variable over this region (Sidibe *et al*., 2020).

Materials and methods

Study area

The humid tropical region of Nigeria is located from longitude 3° E to 12°E and latitude 4°N to 9°N, within the Guinea Coast zone of West Africa (Ogungbenro and Morakinyo, 2014; Akinsanola *et al.*, 2016). The region accommodates about 53.5% of the country's population and accounts for about 30% of the country's total land area (FRNOG, 2007). There is a wide diversity of cultures among the people, who are predominantly farmers with about 72.4% labor force participation rate to the population (UNDP, 2015; Nwokocha *et al.*, 2018). The humid rainforest, derived savanna and southern Guinea savanna agroecological zones of Nigeria, noted for the country's major yam production, are located within this region (Dania *et al.*, 2019). Yam production archives for Anambra, Benue, Delta, Ekiti, Ondo and Taraba states, respectively, within the region were analyzed. The choice for the locations is based on their being the foremost in output (Kolombia *et al.*, 2017; Bergh *et al.*, 2019). The rot incidence survey was carried out in Imo state located within the region. This location is remote from the production locations as the yam wares should have been exposed to handlings during storage and transport. Also, the choice of the metropolitan State is vital to the frequency in the yam ware supply. However, the entire region has similar climate conditions, soil characteristics and a representative crop and soil management (Dania *et al.*, 2019). It is also influenced by the localized convection and variability of the West African monsoon, which supports the rainfall onset in May and its cessation in October (Sanogo *et al.*, 2015). Figure 1 shows humid tropical Nigeria indicating the selected state with their climatological mean (1979–2018) of annual rainfall and the three agroecological zones, respectively.

Yam production outputs

The Food and Agriculture Organization of the United Nations (FAO) archives the yearly output of national yam production for member countries. Production is defined as comprising both the quantities of yam sold in the market and those consumed or used by the farmers, recorded in metric tons (FAO, 2019). The production data for Nigeria from 1979 to 2018 were retrieved from https://fao.org/faostat/en/#data. However, records of Nigeria's yam production output vary between the FAO and Nigeria National Bureau of Statistics (NBS) as both datasets were prepared independently, with varying methods (Bergh *et al.*, 2019). The NBS outputs archive for each of the Administrative States in Nigeria from 1995 to 2006 were retrieved from https://nigerianstat.gov.ng/. The NBS is used to validate the FAO at each of the foremost production locations selected in this study.

Rainfall

Observational monthly rainfall data were obtained from the Climatic Research Unit (CRU) version 4.01 at 0.5° by 0.5° horizontal grids over land areas (Harris and Jones, 2017). The choice of CRU is based on it being gage only observation data, whereas, it has extensively been validated over the region with the results indicating its outstanding performance (Okoro *et al.*, 2014; Akinsanola *et al.*, 2016; Sun *et al.*, 2018). In this study, we analyzed the period from 1979 to 2018, from when the CRU observations network was improved and the satellite observations could validate the quality of the datasets (Sun *et al.*, 2018).

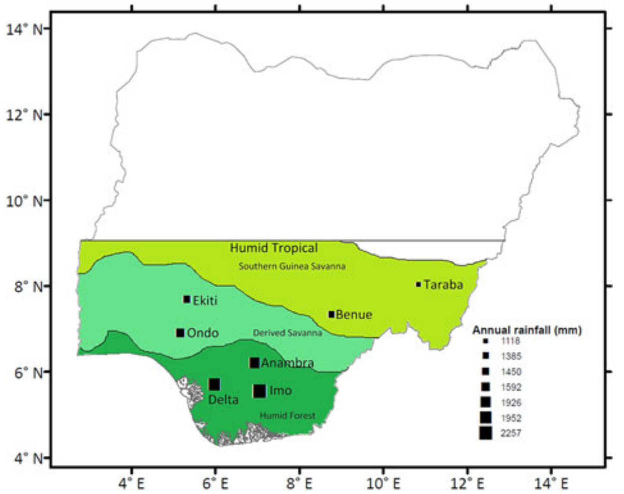

Fig. 1. Humid tropical Nigeria (delineated below thin horizontal line) indicating the selected state locations with their annual rainfall (mm) climatological mean from 1979 to 2018 (solid squares), and the three agroecological zones, respectively (shaded).

CORDEX-Africa

The models' monthly outputs of rainfall were retrieved from the Earth System Grid Federation data nodes (https://esgfindex1.ceda.ac.uk/projects/esgf-ceda/). The five RCMs within the CORDEX-Africa domain that participated in similar experiments' and have outputs for the appropriate variables were selected (Giorgi and Gutowski, 2015). The historical experiment outputs from 1979 to 2005 have been examined for performance evaluation. The bias-corrected (see Section 'Data analysis') projection outputs of the representative concentration pathway (RCP) 4.5 and 8.5 experiments from 2006 to 2050 were analyzed, respectively. The RCP 4.5 and RCP 8.5 were selected based on their representation of the moderate and extreme climate change scenarios, respectively (Meinshausen *et al.*, 2011). Further descriptions of the selected models are presented in Table 1.

Sampling survey and rot incidence

The monthly field survey for white yam (*Dioscorea rotundata* Poir) rot incidence was carried out from January to December in 2018 at four selected major foodstuff markets in the Owerri metropolis of Imo state. Using simple random selection we acquired 100 tubers of yam by lottery method in each of the four markets, respectively, summing a total of 400 tubers of yam examined in each month. The choice of the yam species is based on it being the most cultivated and the most consumed, locally (Dania *et al.*, 2016; Bergh *et al.*, 2019). The market serves as a functional storage facility to edible yam across the country and accommodates products originating from the foremost production locations, round the year. Personal communications with the traders confirm that a yam ware do not last more than 2 weeks in stock and they were sourced from the farmers located in the major yam producing locations. It is noteworthy that both the marketers and the farmers share grave loss experiences due to the rot. Recently, cities have served as major outlets for yam

Table 1. List of the CORDEX-Africa models, their descriptions and references

RCM name	Institute ID/name	Downscaling realization	Lon.	Lat.	Horizontal resolution	Experiment	Driving GCM	Ref.
CCLM4-8-17	CLMcom/Climate Limited-area Modeling Community (CLM-Community)	v1	194	201	0.44° × 0.44°	Historical	CNRM-CERFACS-CNRM-CM5	Panitz *et al.* (2014)
						RCP 4.5		
						RCP 8.5		
RCA4	SMHI/Swedish Meteorological and Hydrological Institute, Rossby Centre	v1	194	201	0.44° × 0.44°	Historical	MPI-M-MPI-ESM-LR	Samuelsson *et al.* (2011)
						RCP 4.5		
						RCP 8.5		
REMO2009	MPI-CSC/Helmholtz-Zentrum Geesthacht, Climate Service Center, Max Planck Institute for Meteorology	v1	194	201	0.44° × 0.44°	Historical	NOAA-GFDL-GFDL-ESM2M	Jacob *et al.* (2012)
						RCP 4.5	ICHEC-EC-EARTH	
						RCP 8.5	MIROC-MIROC5	
HIRHAM5	DMI/Danish Meteorological Institute, Copenhagen, Denmark	v2	194	201	0.44° × 0.44°	Historical	ICHEC-EC-EARTH	Maule (2014)
						RCP 4.5		
						RCP 8.5		
RACMO22T	KNMI/Royal Netherlands Meteorological Institute, De Bilt, The Netherlands	v2	194	201	0.44° × 0.44°	Historical	MOHC-HadGEM2-ES	van den Hurk *et al.* (2014)
						RCP 4.5		
						RCP 8.5		

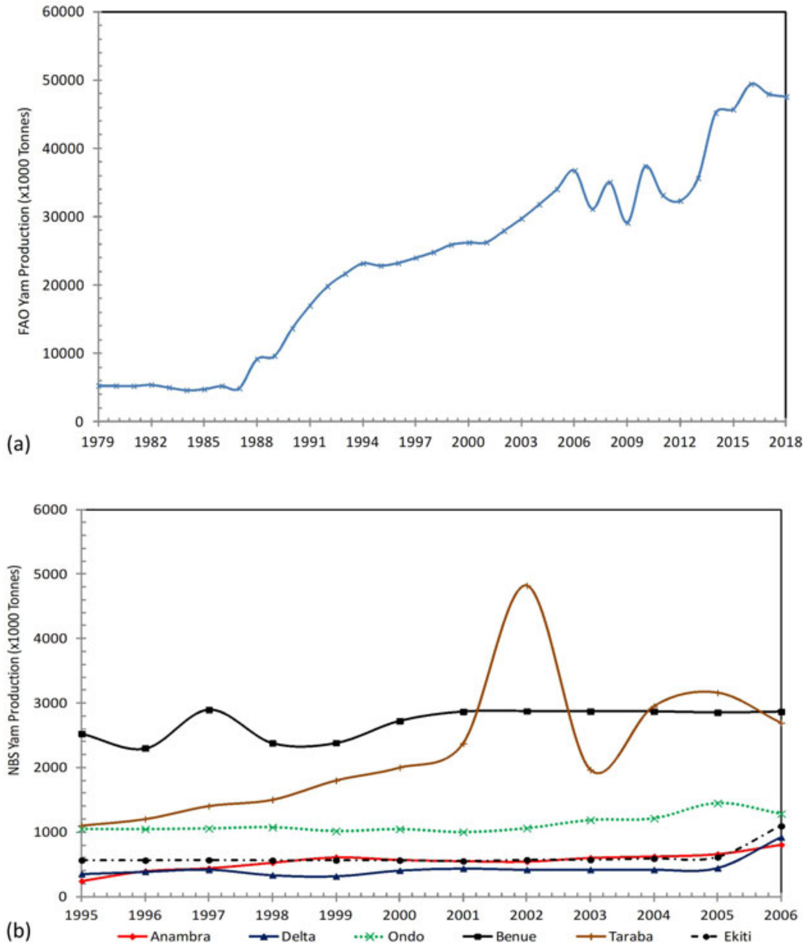

Fig. 2. Time series of (a) FAO national annual yam production (tons) output for Nigeria from 1979 to 2018, and (b) NBS annual yam production (tons) data for the states from 1995 to 2006.

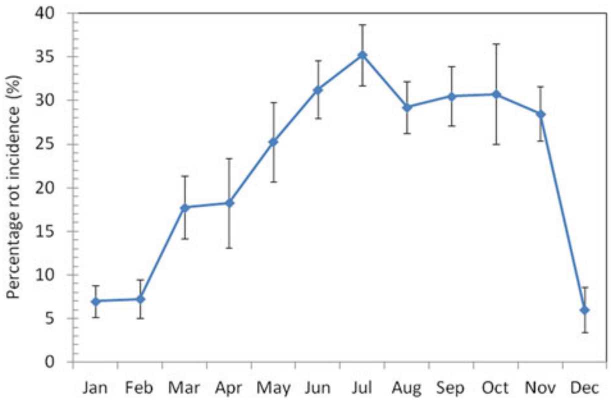

Fig. 3. Monthly percentage (%) of yam rot incidence from January to December 2018. The error bars indicate the s.d. of the percentage rot incidence in each month, respectively.

commercialization whereas the consumption fuels the expansion in its production (Amegbeto *et al*., 2008; Kolombia *et al*., 2017).

The percentages of rot incidence per month on the examined yam samples were computed as,

$$\text{Percentage rot incidence (\%)} = \frac{\text{Total number of diseased samples per month}}{\text{Total number of examined samples per month}} \times 100. \qquad (1)$$

Table 2. Average population of the pathogenic fungi isolates from the rotted tubers expressed in CFU per 10 ml of water

Isolates	Average number of colonies	CFU per 10 ml
B. theobromae	16.3	16.3×10^3
Aspergillus flavus	15.4	15.4×10^3
Rhizopus stolonifer	13.2	13.2×10^3
F. oxysporum	11.8	11.8×10^3

Pathogenicity and proximate composition analysis

The diseased tissue, identified after cutting through a tuber, is typically brown and as the disease progresses the regions first infected turns darker and water-soaked lesions occur (Ogundana *et al*., 1970; Amegbeto *et al*., 2008). The diseased samples were isolated and subjected to pathogenicity tests to confirm rots using the methods described in Ezeonu *et al.* (2018) and Dania *et al.* (2019) for the fungi pathogen-induced rots, Shiriki *et al.* (2017) for the bacteria pathogen-induced rots and Kolombia *et al.* (2020) for the nematode induced rots. Both the healthy and the diseased samples were compared for nutritional composition using the proximate analysis methods described in Bekele and Bekele (2018).

Table 3. Average population of the pathogenic bacteria isolates from the rotted tubers expressed in CFU per 10 ml of water

Isolates	Average number of colonies	CFU per 10 ml
E. carotovora	4.86	4.86×10^3
P. aeruginosa	3.71	3.71×10^3
K. oxytoca	3.31	3.31×10^3

Table 4. Average population density of pathogenic nematode species extracted from the peel of the rotted tubers

Species	Frequency of occurrence (%)	Population of Nematode
Scutellonema	21.25	1038
Platylenchus	16.50	815
Meloidogyne	10.75	391
Rotylenchus	8.75	213
Aphelenchus	5.75	108

Data analysis

The 12-month standardized precipitation index (SPI), which reflects the long-term annual rainfall variability over the region, is calculated using the gamma-to-normal distribution described in WMO (2012). The characteristic impact (Wei *et al.*, 2016) of the variations in the monthly rainfall over the region on the percentage of yam rot incidence is estimated, assuming a linear relationship, as

$$\kappa = \frac{\partial(\%\ \text{rot incidence})}{\partial(R)} \times \sigma(R), \tag{2}$$

where the value of κ is in percentage rot incidence per month, the first term is a regression coefficient of the monthly rainfall on the percentage rot incidence per month, whereas, the second term is the standard deviation (S.D.) of the monthly rainfall. A positive (negative) value of κ indicates a consequent increase (decrease) in the magnitude of the percentage rot incidence.

Trends of the rainfall variability and the national yam production output were investigated using the nonparametric Sen's slope and were tested for statistical significance using the Mann–Kendall test (Gilbert, 1987). The coefficient of variation (CV) indicates the level of the variability with the climatological means. Assuming a linear dependency for simplicity, the coefficient of correlation (r) value indicates the strength of the relationship between compared datasets while the t-test determines the statistical significance of the value. The mean bias error (MBE) indicates the average deviation as well as the systematic differences between the models' output and the observational.

The bias-correction of the models' output is computed, assuming the MBE to be constant at each grid point, over time, in each model, respectively, using the method described in Nath *et al.* (2017) as

$$\text{Bias-correction} = \frac{\sum_{i=1}^{n} P_{\text{mod}(i)} \pm \text{MBE}}{n}, \tag{3}$$

Table 5. Average percentage (%) composition from proximate analysis on 1 g sample of each yam

Composition	Healthy samples (%)	Diseased samples (%)
Starch	46.3	42.02
Crude protein	5.83	7.02
Crude fiber	2.71	1.84
Ash	1.66	1.43
Fats and oil	0.59	0.21

where P_{mod} is the model output and n is the number of months in the time series. The Kling–Gupta efficiency (KGE) indicates the models' performance to calibration and evaluation, compared to the observation, and is computed as

$$\text{KGE} = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{\text{mod}}}{\sigma_{\text{obs}}} - 1\right)^2 + \left(\frac{\mu_{\text{mod}}}{\mu_{\text{obs}}} - 1\right)^2}, \tag{4}$$

where σ_{obs} and σ_{mod} are the S.D. in the observation and models' simulation, respectively, while μ_{mod} and μ_{obs} are the models' simulation and the observation means, respectively. Assuming the mean states as the benchmark of evaluation, values in the range of $-0.41 < \text{KGE} \leq 1$ are considered 'reasonable' performances, whereas, $\text{KGE} = 1$ indicates a perfect agreement (Knoben *et al.*, 2019).

Results and discussion

Recent yam production status in Nigeria

Differences in the preparation of the production datasets necessitated the representation performance evaluation of the national annual output at various locations. In Figures 2a and 2b the time series of FAO national annual yam production output for Nigeria from 1979 to 2018 and the NBS annual yam production data of the locations from 1995 to 2006, respectively, are shown. The FAO production output indicates an increment with a positive trend of 1157.08×10^3 metric tons of yam production per year, at $\alpha = 0.001$ level of significance from the Mann–Kendall test. The FAO output is validated with the NBS data at the various locations, for the same time scale, to investigate their representation of the national output. From the comparison, the locations show positive r values (Anambra = 0.86; Benue = 0.59; Delta = 0.73; Ekiti = 0.70; Ondo = 0.85; Taraba = 0.57), all significant at 95% confidence level from the t-test. This result indicates that the recent increment in the national annual yam production is adequately replicable in the respective locations.

Rot incidence and the effect on tuber quality

The monthly percentage rot incidence, as observed in Imo state in 2018, is shown in Figure 3 with the error bars indicating the standard deviation (S.D.) of the percentage rot incidence in each month, respectively. The values indicate that July recorded the maximum incidence whereas January and December recorded the least incidences from the survey. To validate rot incidence, the pathogenicity test on the yam samples confirms rot by isolates of fungi, bacteria and nematodes as the virulent pathogens. Table 2 shows the average population of the fungi isolates

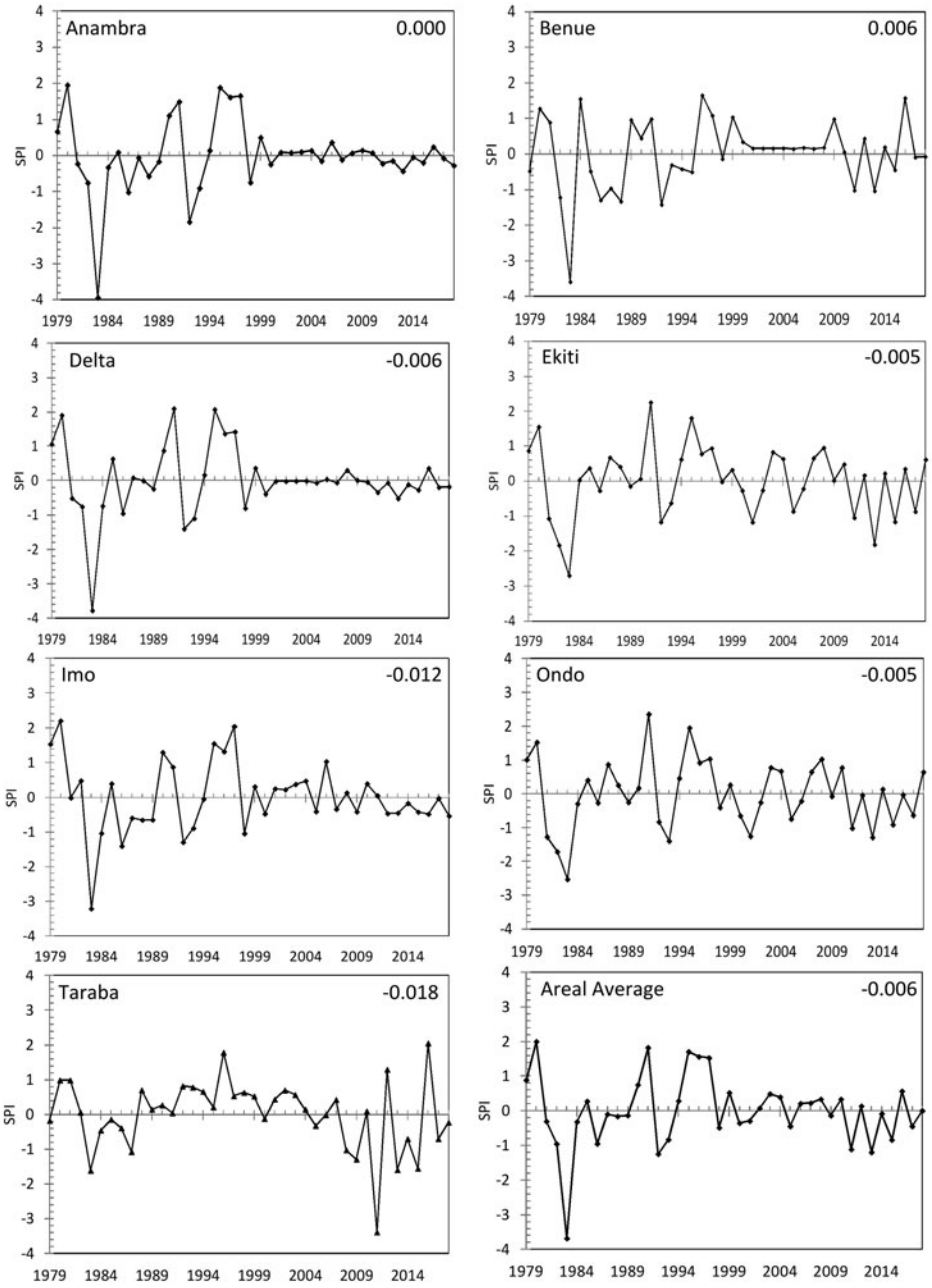

Fig. 4. 12-month SPI of the annual rainfall at the locations and the areal average, respectively. Inserted at the top left corner of each panel is the Sen's slope of the trends.

expressed in colony forming unit (CFU) per 10 ml of water. The *Botryodiplodia theobromae* isolates have the maximum average number of colonies in the rot samples. Table 3 shows the average population of the bacteria isolates also expressed in CFU per 10 ml of water. The *E. carotovora* isolates show most colonies in the samples. Table 4 shows the average population density of the nematode species extracted from the peel of the rotted tubers. The *Scutellonema* species has the maximum frequency of occurrence in the diseased samples. This is linked to the storage conditions as the rate of infection is higher at higher storage temperature whereas poor storage spacing greatly enhances the population (Claudius-Cole *et al*., 2020). The quality of the sampled yams, from the proximate analysis, reveals that the rot diseased samples show deteriorating composition compared to the healthy samples (Table 5). These attributes affect the utilization value of yam tuber (Amegbeto *et al*., 2008).

Rainfall variability and the links with rot incidence and yam production

The 12-month SPI of the annual rainfall over the locations and the areal average from 1979 to 2018 is shown in Figure 4. The Sen's slopes indicate decreasing trends except at Anambra and Benue with increasing trends, respectively. However, the areal average shows a nonsignificant trend from the Mann–Kendall test, which is evident of the Guinea Coast zone (Sanogo *et al*., 2015; Okoro *et al*., 2020). In Figure 5, the trends and CV of rainfall from 1979 to 2018 across the locations were computed for each month, respectively. The July rainfall show decreasing trends at all locations with the areal average indicating the decreasing trend at $\alpha = 0.01$ level of significance from the Mann–Kendall test and less variability (CV = 11.32%). On the contrary, rainfall in December shows increasing trends in most locations with the

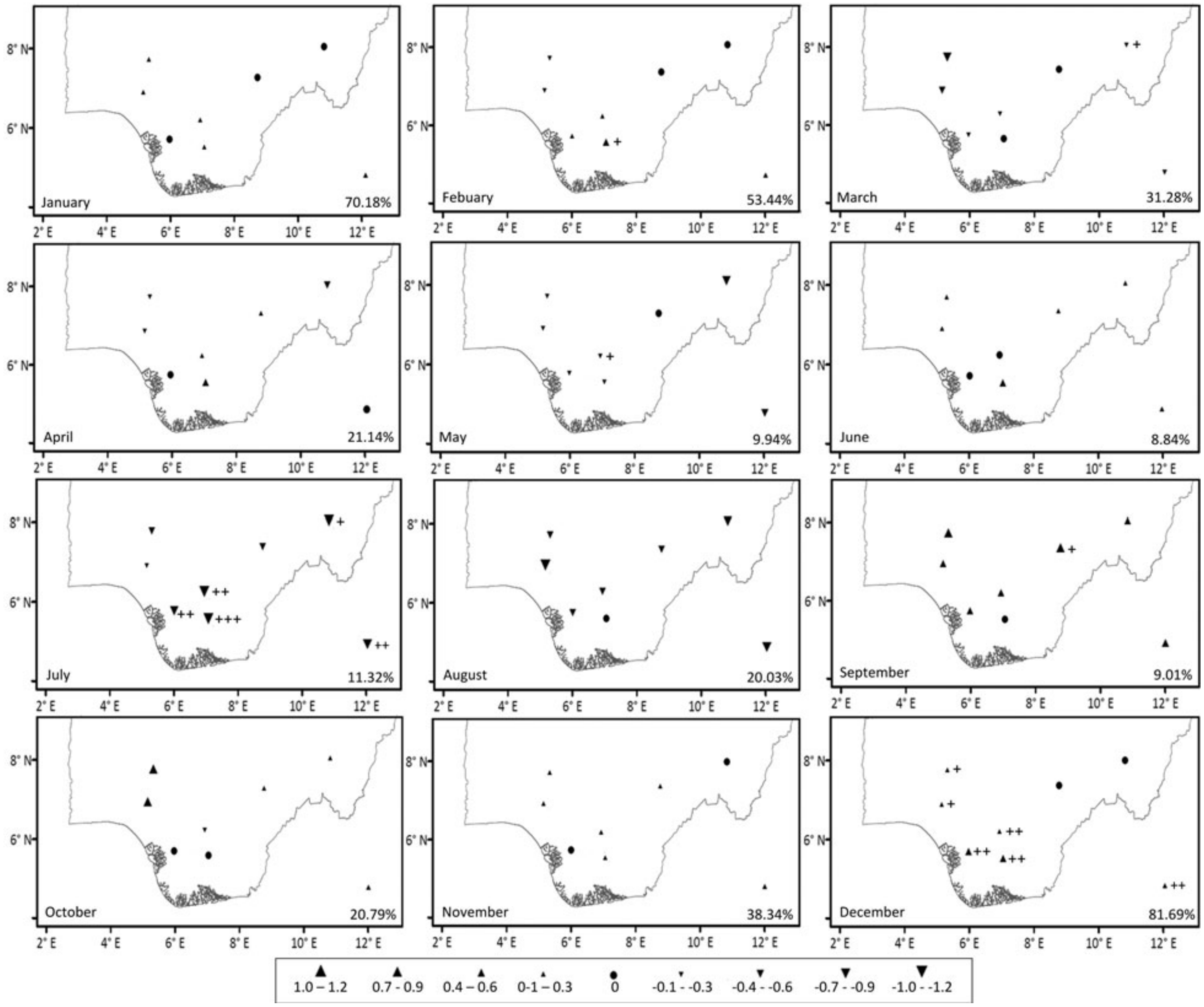

Fig. 5. Temporal trends of CRU monthly rainfall from 1979 to 2018 at the locations and the areal average, respectively. The Sen's slope (▲ = increase; ● = no trend; ▼ = decrease) values (mm yr^{-1}) of the trends are indicated, whereas, the levels of significance (+ at $\alpha = 0.05$; ++ at $\alpha = 0.01$; +++ at $\alpha = 0.001$) are shown. The Sen's slope value (mm yr^{-1}), its significance level, and the CV value (%) for the areal average of each month, respectively, is indicated at the bottom right corner of each panel.

Table 6. Statistical relationship between the monthly percentage (%) yam rot incidence and the monthly rainfall

Location/state	Anambra	Benue	Delta	Ekiti	Imo	Ondo	Taraba	Areal average
r	0.86	0.80	0.85	0.73	0.91	0.76	0.78	0.84
K (% month^{-1})	9.10	8.54	9.02	7.75	9.67	8.12	8.35	8.93

All correlation coefficient (r) values are significant at 99% confidence level from the t-test.

areal average showing the increasing trend at $\alpha = 0.01$ level of significance from the Mann–Kendall test but with high variability (CV = 81.69%).

The statistical linear relationship between the monthly percentage rot incidence and the monthly rainfall at each location and the areal average is indicated in Table 6. The results show the positive correlation values, which are all significant at 99% confidence level from the t-test. Also, the monthly rainfall shows positive characteristic impact values with the percentage rot incidence, which signifies that increase (decrease) in the monthly rainfall corresponds to increase (decrease) in the magnitude of monthly percentage rot incidence. This result corroborates that the lower the natural antioxidants in plants occasioned by high rainfall, the more the rot incidence (Herrera *et al.*, 2017). Hence, the significantly decreased July rainfall over the period (from 1979 to 2018) caused the reduction in the magnitude of percentage rot incidence that occurred in July for the same period. Indeed, this reduction in the magnitude of the July rot incidence guaranteed more healthy yams hence the increment in the country's annual yam production from 1979 to 2018.

Since there is less percentage rot incidence in December coupled with the high CV value in the December rainfall, it is

Table 7. Statistical performance of the historical outputs (1979–2005) in simulating the CRU monthly rainfall variability and the annual rainfall temporal trends

	Monthly rainfall			12-month SPI	
Data	*r*	MBE (mm month^{-1})	KGE	Mann–Kendall *Z* test	Sen's slope (yr^{-1})
CCLM4-8-17	0.80	20.98	−0.01	0.71	0.02
HIRHAM5	0.82	−19.60	0.62	1.38	0.04
RACMO22T	0.86	−13.61	0.51	0.29	0.01
RCA4	0.89	18.67	0.72	0.00	0.00
REMO2009	0.87	−35.80	0.62	0.79	0.03
Ensemble mean	0.92	−5.87	0.79	1.29	0.04
CRU				0.46	0.01

All correlation coefficient (*r*) values are significant at 99.9% confidence level from the *t*-test.

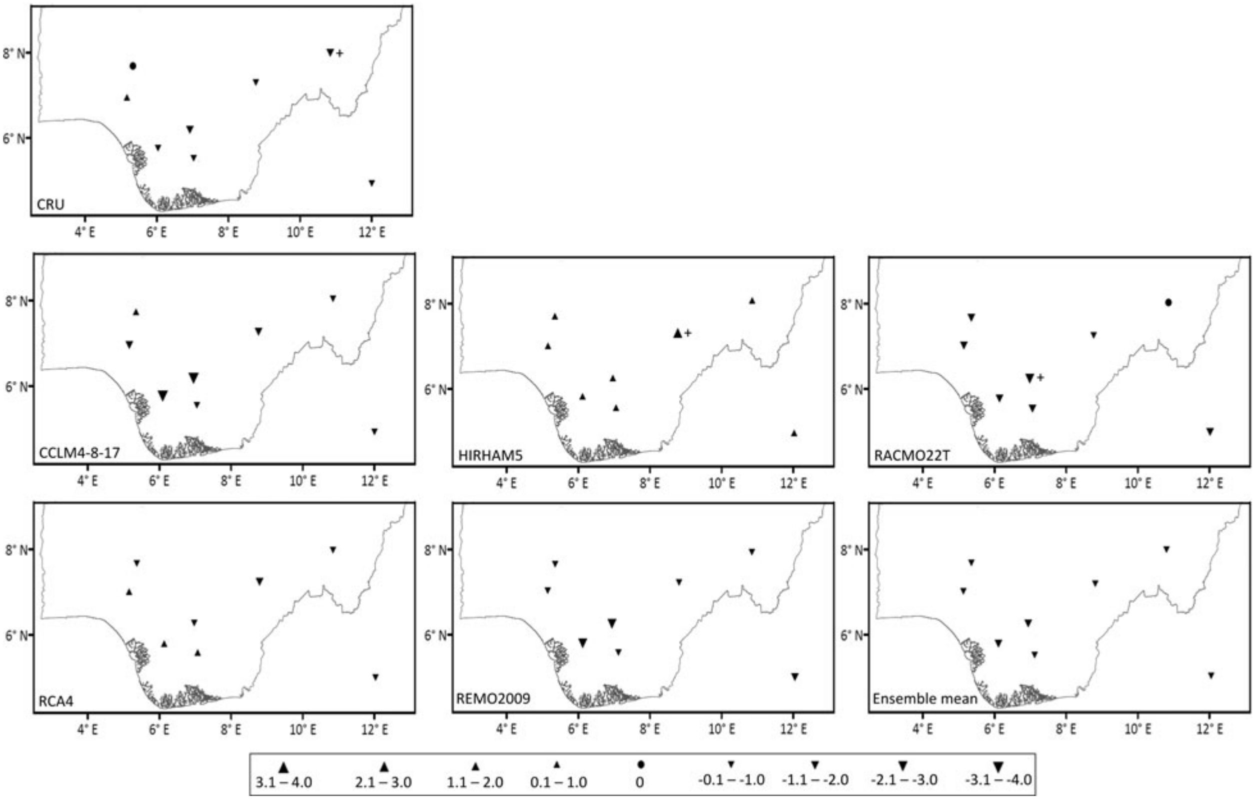

Fig. 6. Temporal trends of July rainfall simulations in historical output from the models and the ensemble mean, and the CRU for the same period. The Sen's slope (▲ = increase; ● = no trend; ▼ = decrease) values (mm yr^{-1}) of the trends are indicated, whereas, the level of significance (+ at $\alpha = 0.05$) is shown. The Sen's slope value (mm yr^{-1}) for the areal average of each month is indicated at the bottom right corner of each panel.

indicative that there exists little or no input to the annual yam production. The linear correlation value ($r = -0.4$, significant at 99% confidence level from the *t*-test) between the July rainfall and the annual yam production within the period corroborates the strong link that exit between them, whereas, that of the December rainfall and the annual yam production ($r = 0.2$, non-significant from the *t*-test) confirms little or no relationship.

CORDEX-Africa projected rainfall variability and the potential link with rot incidence and yam production

The CORDEX-Africa models' performances were evaluated for the region by comparing the ability of the historical experiments' outputs in simulating the CRU monthly rainfall from 1979 to 2005. The statistical results of the comparison are shown in Table 7. The models and their ensemble mean show positive correlation values, which are significant at 99.9% confidence level from the *t*-test. The models and the ensemble mean show negative MBE in simulating the CRU monthly rainfall except for CCLM4-8-17 and RCA4 having positive values. The KGE values indicate that all the models and the ensemble mean show reasonable performance in simulating the CRU monthly rainfall.

Indeed, the models and the ensemble mean agree with CRU in simulating the nonsignificant (from the Mann–Kendall test) positive Sen's slope in the 12-month SPI of the region's interannual rainfall. Also, the results in Figure 6 reveal that the models and

Table 8. Statistical performance of the bias corrected RCP 4.5 and RCP 8.5 outputs, respectively, in simulating the CRU monthly rainfall variability and the annual rainfall temporal trends from 2006 to 2018

	RCP 4.5					RCP 8.5				
	Monthly rainfall			12-month SPI		Monthly rainfall			12-month SPI	
Data	*r*	MBE (mm month^{-1})	KGE	Mann–Kendall *Z* test	Sen's slope (yr^{-1})	*r*	MBE (mm month^{-1})	KGE	Mann–Kendall *Z* test	Sen's slope (yr^{-1})
CCLM4-8-17	0.78	8.83	0.39	2.87^{++}	0.22	0.81	−10.24	0.58	−1.89	−0.16
HIRHAM5	0.84	10.83	0.80	1.40	0.12	0.87	9.92	0.83	−1.04	−0.08
RACMO22T	0.87	−1.34	0.73	−0.92	−0.07	0.87	3.23	0.74	1.16	0.13
RCA4	0.93	0.33	0.81	0.79	0.12	0.91	5.82	0.81	−0.79	−0.09
REMO2009	0.92	31.29	0.76	−0.31	−0.02	0.90	48.99	0.57	0.31	0.02
Ensemble mean	0.95	9.99	0.91	2.62^{++}	0.20	0.96	11.54	0.90	−0.92	−0.09
CRU				−0.79	−0.06				−0.79	−0.06

All correlation coefficient (*r*) values are significant at 99.9% confidence level from the *t*-test.
$^{++}$Signifies at $\alpha = 0.01$ level of significance.

Table 9. Projected 12-month SPI of annual rainfall temporal trends from 2019 to 2050 in the bias corrected outputs of RCP 4.5 and RCP 8.5 experiments, respectively

	RCP 4.5		RCP 8.5	
Data	Mann–Kendall *Z* test	Sen's slope (yr^{-1})	Mann–Kendall *Z* test	Sen's slope (yr^{-1})
CCLM4-8-17	0.57	0.01	−1.67	−0.03
HIRHAM5	−0.24	−0.01	1.93	0.04
RACMO22T	−0.08	0.00	0.79	0.01
RCA4	0.47	0.01	−0.89	−0.03
REMO2009	−1.70	−0.03	0.60	0.01
Ensemble mean	−0.60	−0.02	0.34	0.01

the ensemble mean show outstanding performance in simulating the CRU July rainfall. This is evident as they show negative trends on the areal averages except for HIRHAM5 with a nonsignificant positive trend.

The bias-corrected outputs of RCP 4.5 and RCP 8.5 experiments from the models and the ensemble mean were analyzed. The comparison of their performance in simulating the CRU rainfall from 2006 to 2018 is presented in Table 8. The models and the ensemble mean show outstanding improvements in simulating the CRU monthly rainfall as evident in the correlation and KGE values, respectively, in both RCP 4.5 and RCP 8.5. Also, the improved MBE values of the bias-corrected simulation of the monthly rainfall are presented in RCP 4.5 and RCP 8.5, respectively. However, the models and the ensemble mean show varying polarity and significance of their trends in simulating the bias-corrected 12-month SPI interannual rainfall. In the RCP 4.5, CCLM4-8-17 and the ensemble mean have positive trends (at $\alpha = 0.01$ level of significance from the Mann–Kendall test), whereas, CRU has a nonsignificant negative trend. The remaining models have nonsignificant negative trends except for HIRHAM5 and RCA4. In RCP 8.5, the models and the ensemble mean concurs with CRU in simulating the nonsignificant trend in the 12-month SPI. Nonetheless, RACMO22T and REMO2009 simulate positive trends while the rest have negative trends, in agreement with the CRU.

In Table 9 the trends of the bias-corrected projection for 12-month SPI simulations of the interannual rainfall, between 2019 and 2050, from the RCP 4.5 and RCP 8.5 experiments, respectively, are shown. Both the RCP 4.5 and RCP 8.5 project nonsignificant trends (from the Mann–Kendall test) during the period. In the RCP 4.5, CCLM4-8-17, RACMO22T and RCA4 projects positive trends while HIRHAM5, REMO2009 and the ensemble mean project negative trends. On the contrary, all the models and the ensemble mean project positive trends except for CCLM4-8-17 and RCA4 with negative trends, respectively, in the RCP 8.5. Figures 7 and 8 show the models and the ensemble mean projections of the bias-corrected July rainfall from 2019 to 2050 in RCP 4.5 and RCP 8.5, respectively. The results in Figure 7 reveal that on areal average, projections in RCP 4.5 indicate that all the models and the ensemble mean have nonsignificant (from the Mann–Kendall test) positive trends except for REMO2009 that has a positive trend. Similarly in Figure 8, the projections in RCP 8.5 show the models and the ensemble mean have nonsignificant positive trends except for CCLM4-8-17 and REMO2009 with negative trends, respectively.

Eventually, from the outstanding performances of the bias-corrected output of the models and the ensemble mean, with the majority of the projections indicating positive trends in the July rainfall, it is adequate to state that the magnitude of July percentage rot incidence over the region will increase by the year 2050 if the practices remain business as usual. This increment in the magnitude of percentage rot incidence will consequently imply a decrease in the annual yam production over the region, *vis-à-vis* the country, by the year 2050. Indeed, the differences in the areal averages of both scenarios indicate that the magnitude of percentage rot incidence will be greater in the RCP 8.5 than in the RCP 4.5.

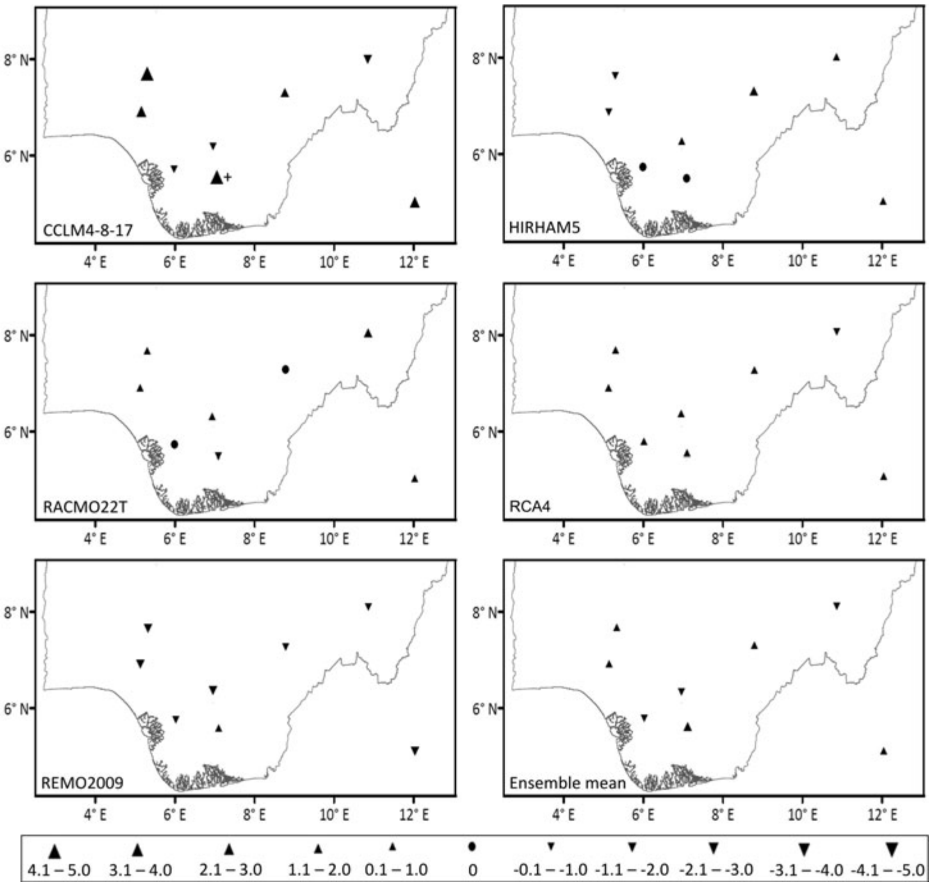

Fig. 7. Projected trends of July rainfall in RCP 4.5 from the models and the ensemble mean from 2019 to 2050. The Sen's slope (▲ = increase; ● = no trend; ▼ = decrease) values (mm yr^{-1}) of the trends are indicated, whereas, the level of significance (+ at α = 0.05) is shown. The Sen's slope value (mm yr^{-1}) for the areal average of each month is indicated at the bottom right corner of each panel.

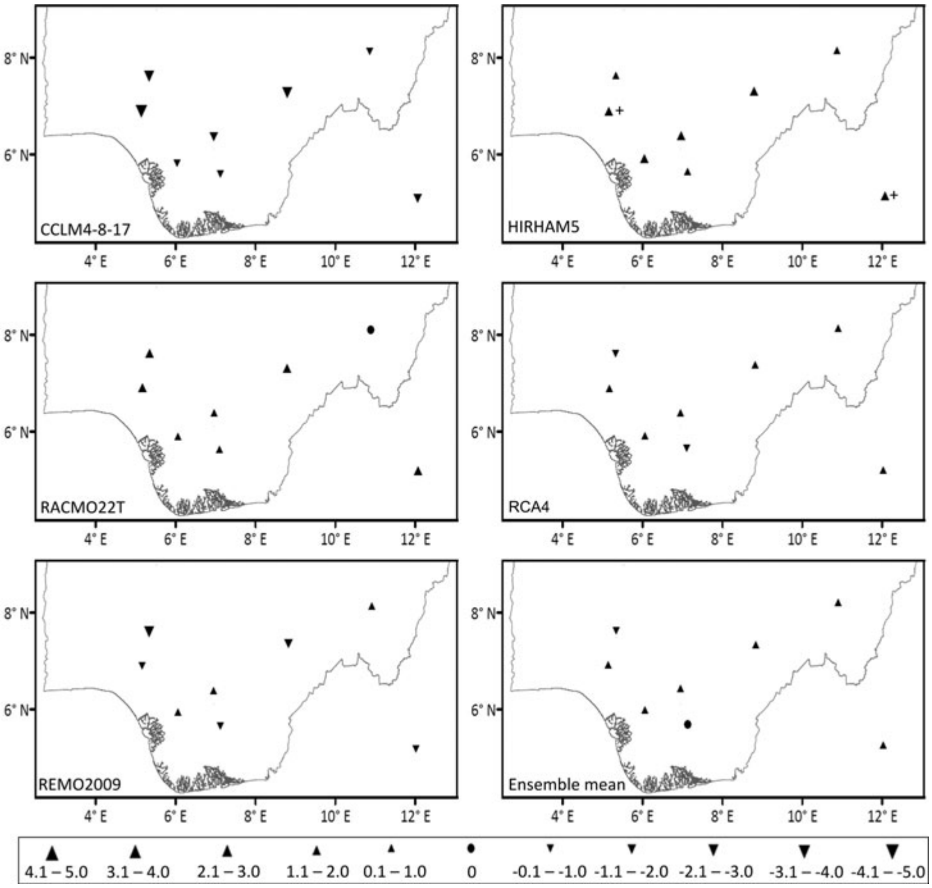

Fig. 8. Projected trends of July rainfall in RCP 8.5 from the models and the ensemble mean from 2019 to 2050. The Sen's slope (▲ = increase; ● = no trend; ▼ = decrease) values (mm yr^{-1}) of the trends are indicated, whereas, the level of significance (+ at α = 0.05) is shown. The Sen's slope value (mm yr^{-1}) for the areal average of each month is indicated at the bottom right corner of each panel.

Uncertainties and limitations of the study

It is noteworthy to state some limitations in this study. First is the limited duration and spatial coverage of the diseased yam sampling for rot incidence. A longer time series and a broader areal coverage would have been desirable. Another limitation is that our study did not investigate the effects from the preservation techniques the yams may have been exposed to, the advancements in the method of yam storage and the improvements in the cultivation processes of the yam tuber. However, the uncertainties associated with this study is mostly on the possible occurring scenarios in the region rainfall variability due to climate change and the emergence of new yam diseases that may be associated with climate change.

Conclusion

Threats from the changing climate are obvious and one of the most vulnerable aspects is on global food security. In an approach to adapt and mitigate this vulnerability, we have analyzed the near-term impact of rainfall variability over humid tropical Nigeria on the percentage rot incidence and the annual yam production output. The FAO annual yam production data for the country from 1979 to 2018 indicate a significant increasing trend. The NBS data for Anambra, Benue, Delta, Ekiti, Ondo and Taraba states, respectively, from 1995 to 2006 validate the FAO submission of increasing production trend. The percentage rot incidences on the sampled yams from the survey indicate its peak occurrence in July. The rots virulent pathogens have been confirmed to be fungi, bacteria and nematodes, whereas, the effect of the rots on the yams composition and quality has been revealed. The CRU monthly rainfall climatology, which shows a nonsignificant decreasing trend in the region's interannual rainfall, indicates a significant decreasing trend in the July rainfall. As observed in 2018, the monthly rainfall showed significant positive correlation values with the percentage rot incidence, whereas, it indicated the positive characteristic impact value with the rot incidences. Therefore, we have deduced that the July rainfall that significantly reduced from 1979 to 2018 consequently reduced the magnitude in percentage rot incidence that peaks in July hence increasing the annual yam production over the region within the period.

The performances of CORDEX-Africa models and their ensemble mean historical outputs in simulating the CRU rainfall from 1979 to 2005 show a good measure of agreement, whereas, the differences are a measure of the uncertainties. The bias-corrected outputs in RCP 4.5 and RCP 8.5, respectively, have been compared with the CRU rainfall from 2006 to 2018 and the results indicate improved 'reasonable' performances. The projected July rainfall from 2019 to 2050 reveals an increasing trend, which indicates the potential increment in the magnitude of percentage rot incidence and consequently the impending decline in the annual yam production. This result is imperative considering the importance of yam as a major staple food and big input for pharmaceutical industries as well as the food insecurity that the decline in yam availability shall cause.

Acknowledgement. This research project is supported by the TETFund (2011–2014 Merged) Institution Based Research Intervention Fund (Ref No. TETFUND/DRSS/UNIV/OWERRI/2015/RP/VOL. 1) of Imo State University, Owerri, Nigeria. The authors are grateful to the research team as well as the anonymous reviewers.

Conflict of interest. There is no conflict of interest.

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