Vol. 13(42), pp. 2275-2284, 18 October, 2018
DOI: 10.5897/AJAR2018.13455
Article Number: DE48AF158897
ISSN: 1991-637X

http://www.academicjournals.org/AJAR

African Journal of Agricultural Research

Full Length Research Paper

Statistical analysis of impact of climate change on crop potentials productivity on a regional scale in Nigeria

K. O. Rauff[1*] and A.A. Ismail[2]

[1]Department of Physics, Faculty of Science, Federal University of Kashere, Gombe State Nigeria.
[2]School of Physics, Universiti Sains Malaysia, 11800 USM, Penang, Malaysia.

Received 11 August, 2018; Accepted 5 September, 2018

Yield improvement is the main aim of all agricultural activities. Therefore, it is important to have an idea about the yield that can be produced from a piece of land before investing in it. This work is aimed at analysing the impact of climate change on crop yield potential and predicting the crop yield potential in six geo political zones in Nigeria using global solar radiation as the only limiting factor of production. Climatic data were obtained from Nigeria Meteorological Agency (NIMET), Oshodi, Nigeria. Results of impact of climate change on the photosynthetic, light-temperature, and climatic potential productivities of maize and their gap differences are presented using a crop growth dynamics statistical method. The results showed that photosynthetic potential productivity decreased from north to south, with the largest values in two maize-growing zones due to higher average growing season radiation and a longer maize growing season. The light-temperature potential productivity of maize was higher than photosynthetic potential productivity, which varied from 3223.99 to 4425.79 kg ha^{-1}, with a mean of 3821.402 kg ha^{-1}; the climatic potential productivity varied from 11279.92 to 29263.75 kg ha^{-1}, with a similar distribution pattern to light-temperature potential productivity with a mean of 23817.32 kg ha^{-1}. The gap between light temperature and climatic potential productivity varied from 6884.07 to 33506.92 kg ha^{-1}, with the high value areas centered in Southern Nigeria.

Key words: Climate change, crop yield potential, global solar radiation, dynamics statistical method, climatic potential productivity, light-temperature potential productivity.

INTRODUCTION

The relation between the atmosphere and the soil cannot be overemphasized. Food production is being influenced by weather and climate variations therefore, studying the impact of climate change is important in order to cater for people as the population of the world is expected to be around 10 billion people by 2100 (Keyzer et al., 2002, Boogaard et al., 2014)). The key parameter that determines food production is crop potential productivity (Wang et al., 2011). Grassini et al. (2009) reported that when a crop is grown under favorable conditions unlike in 2016 in which the earth's surface experienced the warmest climate for the past 135 years (NASA GISS,

*Corresponding author. E-mail: rauffkazeem@yahoo.com. Tel: +601114424190.

2015), it is referred to as potential yield. Yang et al. (2010) and Zheng-Hong et al. (2017) defined photosynthetic light-temperature and climatic potential productivity as when there is maximum crop output determined by radiation, light-temperature, and light-temperature-precipitation conditions, respectively. Crop growth models which we use to estimate agriculture potential and to forecast crop yield are important tools of interdisciplinary research (Zunfu et al., 2017). The essential input variable to estimate potential productivity and actual evapotranspiration is global solar radiation (H_0), but there has been a significant challenge. Despite the fact that remote sensing technique makes H_0 data available to users, the use of empirical models to estimate H_0 from measured meteorological variables is still relevant in many applications (Chen et al., 2013). Many formulas were developed so as to choose the best selection method to tackle these challenges and some of these formulas have been incorporated into crop models as part of the software package (Donatelli et al., 2003), so as to facilitate the preparation of the necessary weather data. The concern of the general community is our climate variation and its impact on our food production. There is need to develop a statistical tool that can assist the farmers (Keating et al., 2003) to forecast the production even before going to the farm. Some studies (Chen et al., 2013) have estimated the spatiotemporal changes in crop potential productivity using various approaches. The generally acceptable method (Supit et al., 1994) used to calculate evapotranspiration is the Penman approach. Penman (1948) was the first to describe evapotranspiration in physical mathematical terms. He calculated evaporation from free-water surfaces, wet bare soil and low grass swards for 10-day periods (Foken, 2008).

METHODOLOGY

Penman Equation 1 consists of two parts: the radiative that calculates the net absorbed radiation and the aerodynamic that calculates the evaporative demand of the atmosphere and the resulting equations are used to calculate the potential evaporation.

$$ET = WH_n + (1-W)E_a \tag{1}$$

Where, ET = the evapo(transpi)ration (mm d^{-1}); H_n = the net absorbed radiation in equivalent evaporation (mm d^{-1}); W = the temperature related weighing factor; and E_a = the evaporative demand in equivalent evaporation (mm d^{-1}).

Preparatory calculations

The average temperature is equal to the air temperature (T) which is calculated as.

$$T = \frac{T_{\max} - T_{\min}}{2} \tag{2}$$

Where, $T_{\max}$ = the maximum temperature (∘C); $T_{\min}$ = the minimum temperature (^{o}C); and T = the average daily air temperature (∘C).

The difference between maximum and minimum temperature is used to calculate the empiric constant of the wind function in the Penman equation.

$$\Delta T = T_{\max} - T_{\min} \tag{3}$$

Where, ΔT = the temperature difference (∘C)

The wind-speed dependency is incorporated in the evaporative demand as the wind speed measured at a height of two meters, and multiplied by an empirical coefficient which is temperature dependent and it is calculated as.

$$BU = 0.54 + 0.35\frac{\Delta T - 12}{4}, \quad \Delta T \geq 12^0 C \tag{4}$$

$$BU = 0.54, \quad \Delta T \leq 12^0 C \tag{5}$$

Where, BU = the empirical coefficient in the wind function.

Saturated vapor pressure is related to mean daily air temperature (Goudriaan, 1977) and given as,

$$e_s = 0.61078 \cdot \exp\left(\frac{17.2693882 \cdot T}{T - 35.86 + 273.16}\right) \tag{6}$$

Where, e_s = the saturated vapor pressure (hPa); and T = the air temperature (∘C).

Terms in the Penman Formula

The temperature related weighing factor W in Equation 1 is defined (Penman, 1948) as,

$$W = \frac{\Delta}{\Delta + \gamma} \tag{7}$$

Where, Δ = slope of the saturation vapor pressure curve $\left(hPa^{o}C^{-1}\right)$, γ = the psychometric constant $\left(hPa^{o}C^{-1}\right)$.

The evaporative demand of the atmosphere depends on the difference between saturated and actual vapor pressure and on the wind function.

$$E_a = 0.26\left[(e_s - e_a)(f_c - BU \cdot u(2))\right] \tag{8}$$

Where, E_a = the evaporative demand (mm d^{-1}); e_s = the saturated vapour pressure (hPa); e_a = the actual vapour pressure(hPa); f_c = the empirical constant; BU = the coefficient in wind function; and u = the mean wind-speed (m s^{-1}).

For crop canopies f_c = 1.0 and for a free water surface f_c = 0.5 are assumed, Eq. 1 becomes.

$$ET = \frac{\Delta H_n + \gamma E_a}{\Delta + \gamma} \quad (9)$$

Where: ET = the pan evaporation in (mmd^{-1}); H_n = the net absorbed radiation (mmd^{-1}); Δ: the slope of the saturation vapor pressure versus air temperature (hPa^oC^{-1}); γ = the psychometric constant $0.49\ mm$ of $Hg\ /^o\ C$ or $0.667kPa/K$; and E_a = the evaporative demand (mm d^{-1}).

Methods used to estimate global radiation

Solar radiation is one of the meteorological factors determining potential productivity (Boisvert et al., 1990). This can be estimated (Ångström, 1924) from other climatic variables; for example from sunshine duration; air temperature range (De Jong and Stewart, 1993), precipitation (De Jong and Stewart, 1993) and cloud-cover (Barker, 1992). We used the equation postulated by Ångström (1924) and modified by Prescott (1940).

$$\frac{H_h}{H_0} = a + b\frac{n}{N} \quad (10)$$

Where, H_h = the monthly average daily global radiation on a horizontal surface $(MJ \cdot m^{-2} \cdot day^{-1})$; H_0 = the monthly average daily extraterrestrial radiation on a horizontal surface $(MJ \cdot m^{-2} \cdot day^{-1})$; n = the monthly average daily number of hours of bright sunshine; N = the monthly average daily maximum number of hours of possible sunshine (or day length); and a and b = the regression constants.

This above named equation is the most widely used empirical equation which estimates global solar radiation from sunshine hour duration.

Daily climate data from sixteen (16) stations of the Nigeria Meteorological Agency (NIMET) Oshodi, Nigeria were obtained. The climate data are of high quality. The data include Sunshine Hours (h), Average Temperature (∘C), Maximum Temperature (∘C), Minimum Temperature (∘C), Precipitation (mm), Relative Humidity (%), and Wind Speed (ms^{-1}) over the period of 30 years (1985 to 2014). In estimating crop yield potential, the study areas were divided into three maize-growing districts based on different sowing dates and growth periods. Observed maize phenology from the Institute of Agricultural Research and Training (IAR&T) meteorological station was used to calibrate the maize-growing districts.

Calculation of maize potential productivity

Crop potential productivity is calculated according to the crop growth dynamics statistical method, which divides the potential production into three levels: photosynthetic, light-temperature, and climatic potential productivity (Yuan et al*.,* 2012). The photosynthetic potential productivity (PPP; 10^3 kg ha^{-1}) is calculated as,

$$PPP = \sum_{j=1}^{4}\left(\sum_{i=1}^{dl_i}\left(0.219 \times C \times H_h\right)\right) \quad (11)$$

Where, 0.219 = the Huang Bingwei coefficient in unit of $10^{-5}kgkJ^{-1}$; C = the crop economic coefficient, taking the value of 0.4 (Li et al*.,* 2009); *j* represents each maize development stage; dl_i = the length of each crop development stage; H_h = the daily shortwave radiation during the crop growing season in unit of $kJ \cdot cm^{-2} \cdot day^{-1}$.

The light-temperature potential productivity (LTPP; 10^3 kg ha^{-1}) is calculated by correcting the Photosynthetic Potential Productivity with the Temperature Stress Coefficient.

$$LTPP = \sum_{i=1}^{4}\left(\sum_{i=1}^{dl_i}\left(0.219 \times C \times H_h \times f(T)\right)\right) \quad (12)$$

Where, $f(t_i)$ = the temperature stress coefficient that can be calculated as follows.

$$f(T) = \begin{cases} 0 & T \le T_{\min} \\ & T \ge T_{\min} \\ \dfrac{T - T_{\min,}}{T_0 - T_{\min,}} & T_{\min} \le T \le T_0 \\ \dfrac{T_{\max} - T}{T_{\max} - T_0} & T_0 \le T \le T_{MAX} \end{cases} \quad (13)$$

Where, T = the daily average temperature in (^OC); $T_{\min}$, $T_{\max}$, and T_o = the minimum, maximum, and optimum temperatures (^OC) for each crop development stage, respectively.

The climatic potential productivity (CPP; 10^3 kg ha^{-1}) is calculated by correcting the light temperature potential productivity with the water stress coefficient.

$$LTPP = \sum_{i=1}^{4}\left(\sum_{i=1}^{dl_i}\left(0.219 \times C \times H_h \times f(T) \times f(w_j)\right)\right) \quad (14)$$

Here, $f(w_j)$ = the water stress coefficient is calculated as,

$$f(w_j) = \begin{cases} \dfrac{P_j}{ET} & 0 \le P_j \le ET \\ 1 & P_j \ge ET \end{cases} \quad (15)$$

Where, P_j = the total precipitation (mm) during each maize development stage; ET = the total crop water requirement (mm) during each crop development stage, which can be calculated as shown in Equation 1.

RESULTS AND DISCUSSION

The results of photosynthetic potential productivity (PPP), light-temperature potential productivity (LTPP), climatic potential productivity (CPP) and gap differences for the six geo political zones in Nigeria are presented in Table 1 while the geographical map of the area of study is presented in Figure 1.

The geographical information of photosynthetic potential productivity (PPP); light-temperature potential productivity (LTPP) and climatic potential productivity (CPP) are presented in Figures 2, 4 and 6 while their values are presented in Figures 3, 5 and 7 respectively; Figure 8 shows the trend pattern of their gap difference.

The potential productivity and potential productivity gap evaluation is important in order to understand the effect of temperature, rainfall and light resources on crop production. In this study, we analyzed the variations in climate factors and their impact on crop (maize) potential productivities (photosynthetic, light-temperature, and climatic) in six geo-political zones of Nigeria for 30 years between 1985 and 2014, and then quantified the spatial and temporal variations in the gap between light temperature and climatic potential productivity. The highest values of maize potential productivity occurred in North-Eastern and North-Western states. In general, PPP decreases from North to South, with the largest values in maize-growing zones II and III (Bauchi, Yola, Kaduna and Kano states) due to higher average growing season radiation and a longer maize growing season as shown in Figure 2. The spatial change in maize potential productivity did not follow a decreasing trend with latitude due to the complex topographic conditions in these regions. The distribution of areas with high values of photosynthetic potential productivity was different from that with high values of light-temperature productivity due to change in altitude. Areas with high values of photosynthetic productivity were mainly located in the North-Eastern and North-Western regions; however, those with low values of light-temperature potential productivity were mainly located in Southern region of Nigeria. Figure 3 depicts the photosynthetic potential productivity (PPP) of maize that varied from 1091.03 kg to 1505.37 kg ha^{-1}, with a mean of 1294.78 kg ha^{-1} and the highest values of PPP occurred both in the northwest and northeast; whereas the lowest values occurred in the south-south and south-east of the six geopolitical zones in Nigeria. It was noticed that both the PPP and LTP productivities followed the same patterns where the lowest values were recorded in both the south east and south-south of Nigeria as presented in Figure 4. Light-temperature potential productivity of maize was noticeably higher than photosynthetic potential productivity, which varied from 3223.99 to 4425.79 kg ha^{-1}, with a mean of 3821.402 kg ha^{-1} as it has been shown in Figure 5. Figure 6 presents the geographical information of climatic potential productivity (CPP) of the six geopolitical zones of the area of study. Climatic potential productivity varied from 11279.92 to 29263.75 kg ha^{-1}, with a mean of 23817.32 kg ha^{-1}. Figure 6 exhibits the climatic potential productivity variations which decrease in the Northeast of Nigeria, whereas it increases in the Southwest of Nigeria. The gap between light- temperature and climatic potential productivity varied from 6884.07 to 33506.92 kg ha^{-1}, with the high value areas centered in Southern Nigeria as shown in Table 1 and Figure 8, respectively. The gap between light-temperature and climatic potential productivity varied considerably with location (between 6884.07 to 33506.92 kg ha^{-1}) from 1985 to 2014 in Nigeria. Climatic potential productivity was about 10 to 24% of light-temperature potential productivity in these regions, which implies that precipitation is a strong limiting factor for maize potential productivity.

In general, the simulated potential yield decreases generally from north to south due to the latitudinal distribution of solar radiation and growing season temperature which corresponds to the work of Wu et al. (2006). Precipitation during the maize growing season ranges from 412 to 608 mm in different maize-growing districts, which in theory can meet the water requirements of maize. The climatic potential productivity decreases in the northeast of Nigeria, whereas it increases in the southwest of Nigeria. However, a distinct gap between light- temperature and climatic potential productivity exists, varying from 6884.07 to 33506.92 kg ha^{-1}, with the high value areas centered in Southern Nigeria, which presents a maize potential productivity loss due to water stress caused by uneven precipitation distribution during the maize growing season. As presented in Table 1, the

Table 1. The six geo-political zones of Nigeria.

District	Geo-political zones	PPP (kg ha^{-1})	LTPP (kg ha^{-1})	CPP (kg ha^{-1})	Gap Diff
I	North Central States	1400.07	4116.20	18390.89	14274.60
II	North-Eastern States	1495.19	4395.85	11279.92	6884.07
III	North-Western States	1505.37	4425.79	20986.05	16560.26
IV	South-Eastern States	1180.43	3470.48	29263.75	25793.27
V	South-Southern States	1096.59	3223.99	36730.91	33506.92
VI	South-Western States	1091.03	3296.10	26252.41	22956.31

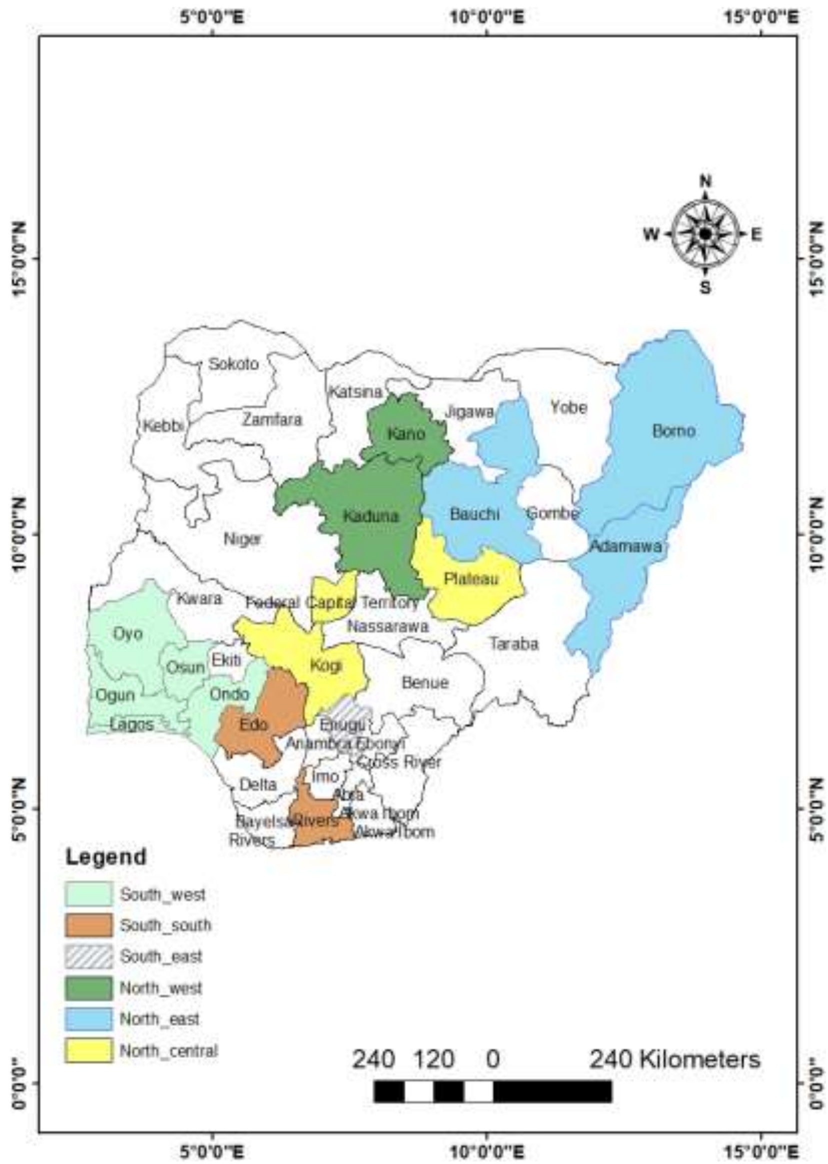

Figure 1. The map of Nigeria showing the six geopolitical zones of area of study. The six Geo-Political Zones of Nigeria where the data were obtained: North Central States: Kogi, Plateau and Federal Capital Territory; North-Eastern States: Borno, Bauchi and Adamawa; North-Western States: Kaduna and Kano; South-Eastern States: Enugu; South-Southern States: Edo and Rivers; South-Western States: Oyo, Ogun, Lagos, Ondo and Osun.

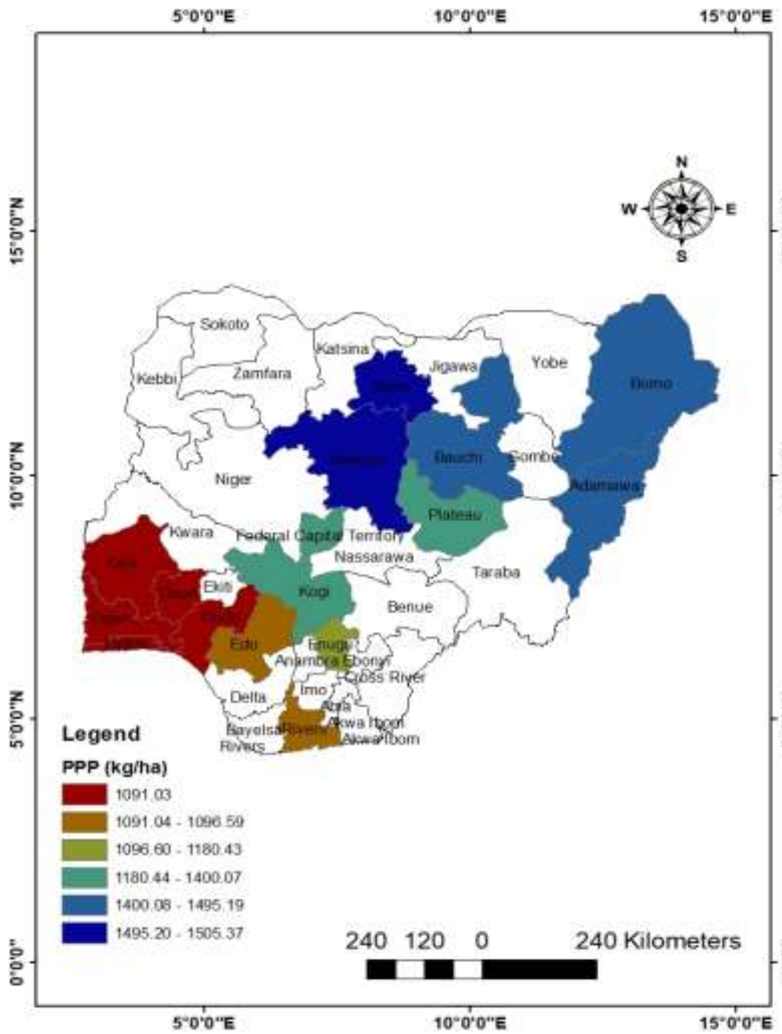

Figure 2. The geographical information of photosynthetic potential productivity (PPP) of the six geopolitical zones of area of study.

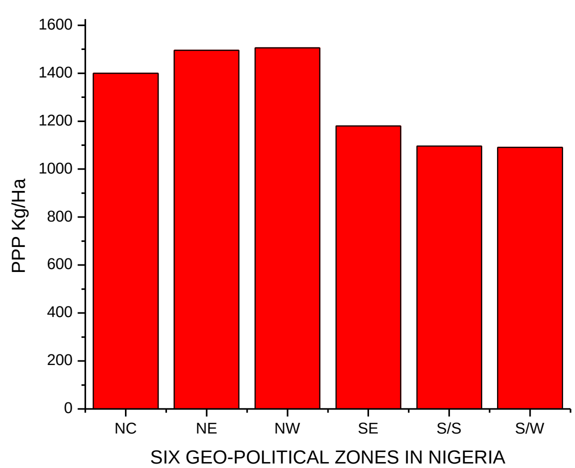

Figure 3. The photosynthetic potential productivity in the six geopolitical zones, Nigeria.

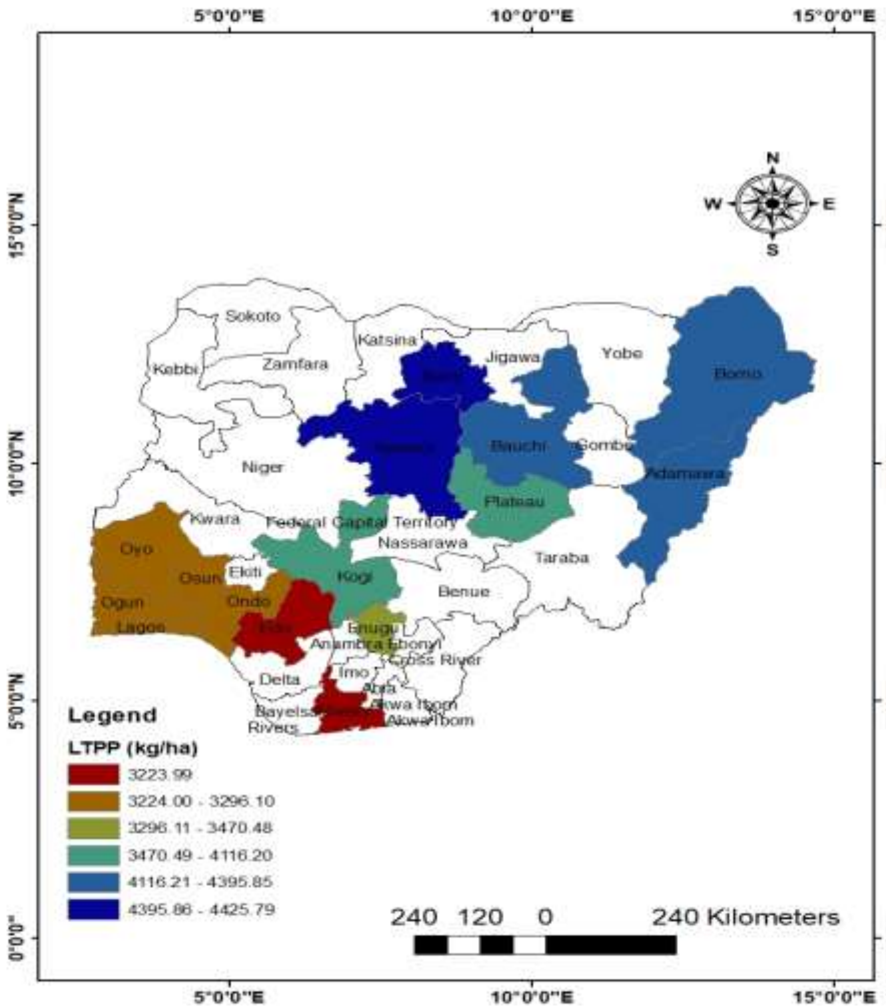

Figure 4. The geographical information of Light Temperature Potential Productivity (LTPP) of the six geopolitical zones of area of study.

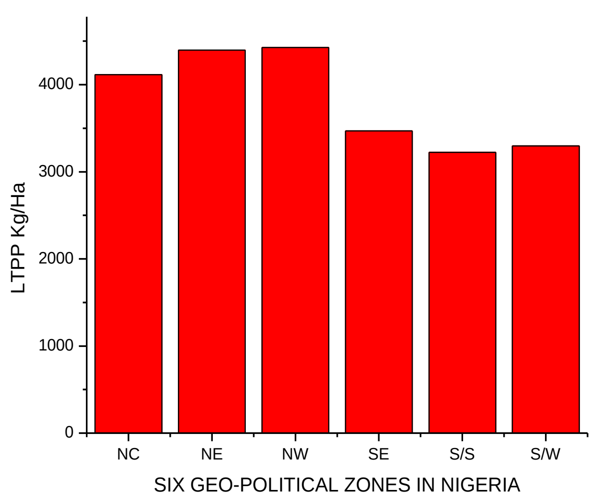

Figure 5. The light-temperature potential productivity in the six geopolitical zones, Nigeria.

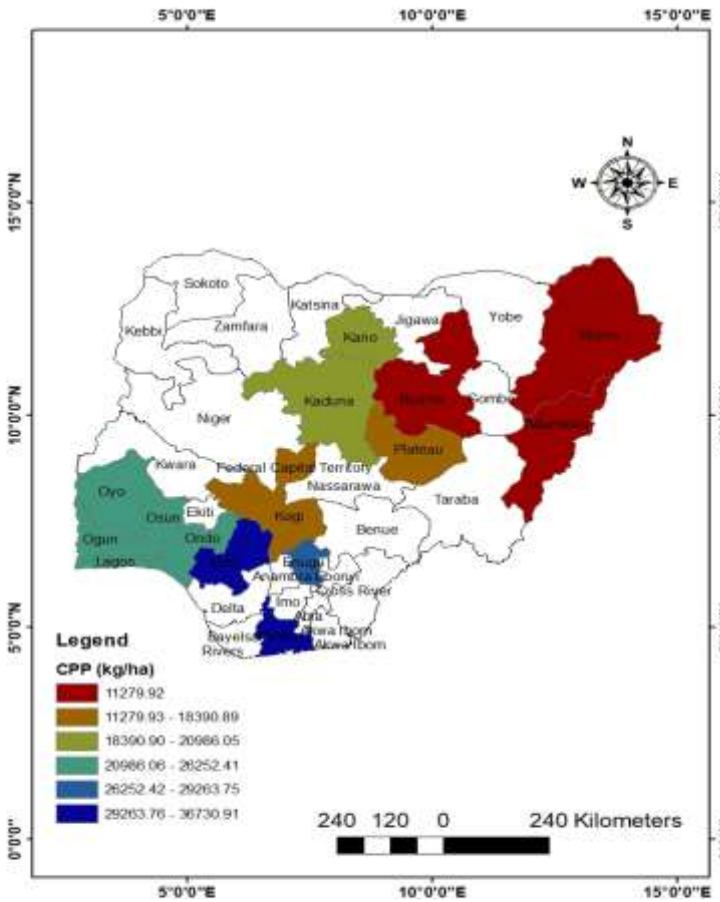

Figure 6. The geographical information of Climatic Potential Productivity (CPP) of the six geopolitical zones of area of study.

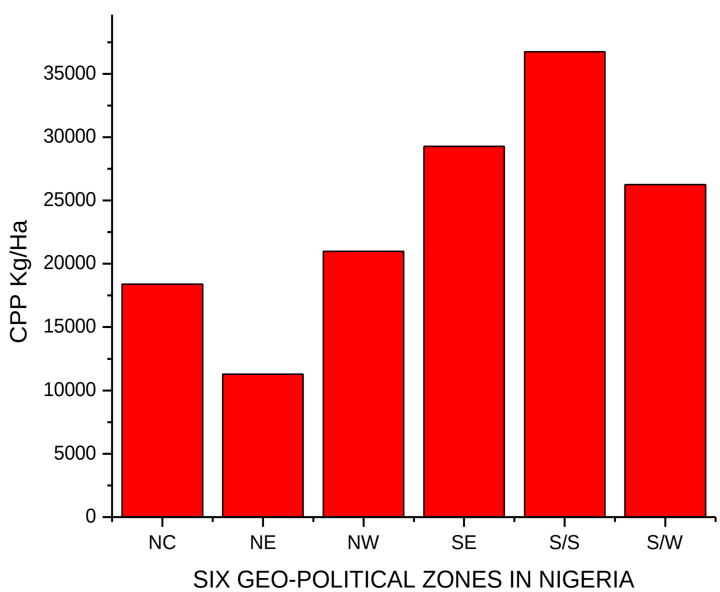

Figure 7. The climatic potential productivity in the six geopolitical zones, Nigeria.

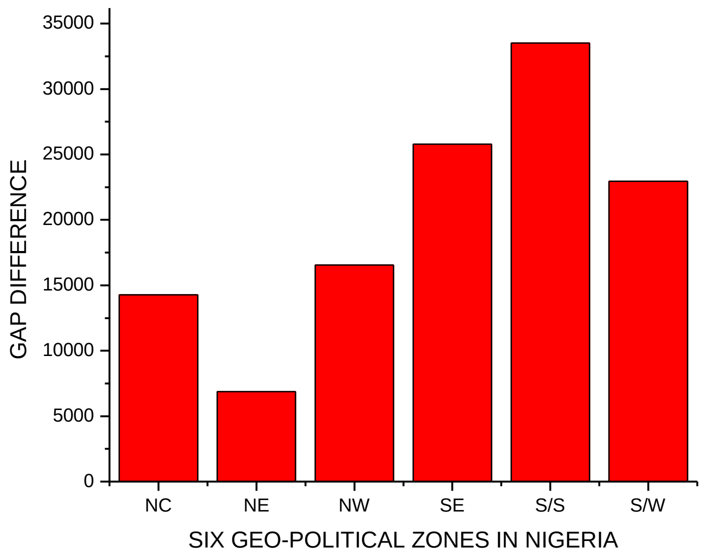

Figure 8. The gap difference in the six geopolitical zones, Nigeria.

largest yield gap was located in south-south and south-east zones.

Conclusion

The major advantage of potential productivity gap analysis is that it is used to know crop yield improvement when there is information about the solar radiation, evapotranspiration, photosynthetic potential productivity (PPP), light-temperature potential productivity (LTPP) and climatic potential productivity (CPP) of the area. Generally, it is a known fact that increases in temperature causes a reduction in climatic potential productivity in the high temperature category, whereas it contributes to an increase in climatic potential productivity at stations in the low temperature category. However, in Northeast, a simulated increase in maximum temperature generally caused a reduction in yield potential, while an increase in minimum temperature produced no significant impact on yield potential. It is noticed that potential productivity is not completely consistent with actual yield. In conclusion, we have demonstrated that a distinct gap between light-temperature and climatic potential productivity exists where annual and growing season precipitation is sufficient when analyzing the impact of climate change on the spatial and temporal variations of maize photosynthetic, light-temperature, and climatic potential productivity from 1985 to 2014 in Nigeria. It is also worth concluding that the geographic information helps to gather actionable intelligence from all types of data.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

REFERENCES

Ångström A (1924). Solar and atmospheric radiation. Quarterly Journal of the Royal Meteorological Society 50:121-126.

Barker HW (1992). Solar radiative transfer through clouds possessing isotropic variable extinction coefficient. Quarterly Journal of the Royal Meteorological Society 118(3):1145-1162.

Boisvert JB, Hayhoe HN, Dubé PA (1990). Improving the estimation of global radiation across canada. Agricultural and Forest Meteorology 52(3-4):275-286.

Boogaard HL, De Wit AJW, te Roller JA, Van Diepen CA (2014). Wofost control centre 2.1; User's guide for the wofost control centre 2.1 and the crop growth simulation model wofost 7.1.7. Wageningen (Netherlands), Alterra, Wageningen University and Research Centre 133 p.

Chen C, Baethgen WE, Robertson A (2013). Contributions of individual variation in temperature, solar radiation and precipitation to crop yield in the north china plain, 1961–2003. Climatic Change 116(3-4):767-788.

De Jong R, Stewart DW (1993). Estimating global radiation from common meteorological variables in Western Canada. Canadian Journal of Plant Science 73(2):509-518.

Donatelli M, Bellochi G, Fontana F (2003). RadEst300: Software to estimate daily radiation data from commonly available meteorological variables. European Journal of Agronomy 18(3-4):363-367.

Foken T (2008). Micrometeorology. Springer-Verlag Berlin Heidelberg 306 p.

Goudriaan J (1977). Crop micrometeorology: a simulation study. simulation monographs. pudoc, wageningen, Netherland 262 p.

Grassini P, Yang H, Cassman KG (2009). Limits to maize productivity in western corn-belt: a simulation analysis for fully irrigated and rainfed conditions. Agricultural and Forest Meteorology 149(8):1254-1265.

Keating BA, Carberry PS, Hammer GL (2003). An overview of apsim, a model designed for farming systems simulation. European Journal of Agronomy 18(3-4):267-288.

Keyzer M, Merbis M, Pavel F (2002). Can we feed the animals? origins and implications of rising meat demand. Paper presented at 2002 International Congress, European Association of Agricultural Economists, Zaragoza, Spain, 28–31 Aug.

National Aeronautics and Space Administration, Goddard Institute for Space Studies (NASA, GISS) (2015). NASA, NOAA Finds 2015 Warmest Year in Modern Record. 18 January. http://www.giss.nasa.gov/research/news/20150116/ (accessed 18 January 2017).

Penman HL (1948). Natural evaporation from open water, bare soil and grass. Proceedings Royal Society Series A 193(1032):120-146.

Prescott JA (1940). Evaporation from a water surface in relation to solar radiation. Transactions of the Royal Society of South Australia 64:114-480.

Supit I Hooijer AA, van Diepen CA (1994). System description of the wofost 60 crop simulation model implemented in CGMS. Volume 1 theory and algorithms, Joint Research Centre Commission of the European Communities EUR 15956 EN: Luxembourg 146 p.

Wang T Lu C, Yu B (2011). Production potential and yield gaps of summer maize in the Beijing-Tianjin-Hebei Region. Journal of Geographical Sciences 21(4):677–688.

Yang J, Peter MV, Jian Y, Michael EG (2010). A Commentary on 'Common SNPs Explain a Large Proportion of the Heritability for Human Height. Twin Research and Human Genetics 13(6):517-524.

Yuan Z, Li J, Zhang L, Gao X, Gao HJ Xu S (2012). Investigation on brca1 snps and its effects on mastitis in chinese commercial cattle. Elsevier 505:190-194.

Zheng-Hong T, Jiye Z, Yong-Jiang Z, Martijn S, Minoru G, Takashi H, Yoshiko K, Humberto RR, Scott RS, Michael LG (2017). Optimum air temperature for tropical forest photosynthesis: mechanisms involved and implications for climate warming 2017. Environmental Research Letters 12:054022

Zunfu L, Xiaojun Liu, Weixing C, Yan Z (2017). A Model-Based Estimate of Regional Wheat Yield Gaps and Water Use Efficiency in Main Winter Wheat Production Regions of China. Scientific Reports 7:6081.