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Suitability Analysis for Yam Production in Nigeria using Satellite and Observation Data

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Abstract

Identification of suitable areas for yam production is critical for ensuring yield in yam production in Nigeria. The study is aimed at determining suitable lands for yam production in Nigeria. Climate, soil, and environmental parameters that have a high contribution to yam production were used in developing a yam production suitability map using the Analytical Hierarchy Process (AHP). The AHP was used in deriving weights through a pairwise comparison technique. According to the findings, highly suitable (HS), suitable (S), marginally suitable (MS), and not suitable (NS) regions accounted for 11.79, 82.68, 4.05, and 1.47% of the study area, respectively. The Normalized Difference Vegetation Index (NDVI), a measure of vegetation vigor, was higher in HS, followed by S regions, and then MS regions. Similarly, climate variables in HS regions were more favorable for plant growth, followed by S regions and MS regions. The correlation between precipitation and temperature is high and significant only in the HS class, despite the fact that NDVI and climate variables are significantly connected in all the suitability classes. The output map, thus determined, provides information on highly suitable, suitable or marginally suitable lands that are of practical importance to agriculturists.

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Keywords: Analytical hierarchy process, Yam production, Nigeria, NDVI, Yield gap, Multi-criterion decision making

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1. Introduction

The United Nations World Food Programme's (UNWFP) live Hunger Map identified about 860 million individuals with insufficient food consumption and a total of 16 countries with very high levels of hunger. Nigeria accounts for 52.9 million (or 6.2%) of the global population with insufficient food consumption [1]. Laganda [2] asserts that of the causes of world hunger, climate change is the one that can be most accurately predicted using scientific tools. It is therefore imperative that scientific knowledge is employed in resolving the global food crisis, beginning with national and/or regional studies, especially for the food crops that thrive in specific regions of the world, such as yam. The emergence of agricultural methods came out as a result of man's quest for food in order to survive, and the agricultural methods have occasionally continued to advance [3].

Yam is a tropical tuber crop that is grown primarily for domestic consumption and commercial use in Africa. Generally, there are several species of yam in the genus *Dioscorea*, but only six are proven to be economically important staple species.

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According to Blench [4], these include *Dioscorea rotundata*, *Dioscorea bulbifera*, *Dioscorea dumetorum*, *Dioscorea alata*, *Dioscorea esculenta*, *Dioscorea cayennensis,* also known as white guinea, aerial, trifoliate, purple, Chinese, and yellow yam, respectively. Awoniyi & Omonona [5], Ike & Inoni [6], confirmed that the most prevalent and economically significant species in Nigeria are *Dioscorea rotundata* and *Dioscorea alata.*

In 2012 and 2019, Nigeria produced approximately 65.00 [7] and 67.34% [8] of the world's yams, which were cultivated on 2.90 [7] and 6.24 million hectares [8], respectively, and were worth billions of dollars. In addition to its value as a staple crop, in Nigeria, yams are a major source of income for most individuals and have tremendous cultural importance because they are employed in numerous religious and cultural rituals. Every year, festivals are held in various cultures to mark the harvest season of yams. Given the current financial crisis Nigeria is facing, upscaling yam production for large scale export can become a major export earner, which will in turn ease pressure on the heavily import-dependent economy. Despite being the world's top producer of yams, there are many factors that contribute to the food crisis in Nigeria. They include: changing climatic variables; shrinkage in size of farm lands due to population increase; poor access to fertilizers and improved varieties; conservative approach to agricultural extension programs and services; obstructive market forces; poor terrain and soil quality; farmers' limited financial resources; disease and pests; and improper timing of planting crops [9–14].

Crop production is influenced by meteorological variables, hence it is important to understand these variables and how they interact in order to determine how they together affect agricultural productivity [15]. Currently, yam is one of the most expensive food items in Nigeria, yet it is also intensely sought after. In addition to improving foreign earnings from exports, the improved production and availability of yams in Nigeria would significantly improve access to food for many Nigerians, as the nation strives towards attaining the Sustainable Development Goal (SDG-2) which aims to eradicate hunger, establish food security and enhanced nutrition, and advance sustainable agriculture. These SDGs can be used as tools for implementing measures that can be used for minimizing the effects of climate change that pose a serious risk to the entire ecosystem [16].

Several studies on agricultural land suitability for production of different crops across Nigeria have been reported by different researchers. For instance, Ikusemoran and Hajjatu [17] studied site suitability for yam, rice and cotton production in Adamawa state, Nigeria. In another study, Kunda and Jajere [18], worked on suitability analysis for agricultural lands in Nasarawa state, Nigeria. Ahmed and Jeb [19], researched on suitability analysis for cultivation of sorghum in Kano state, Nigeria. Zemba et al. [20] reported on suitability analysis for decision-making in cassava cultivation in Adamawa state, Nigeria. Ujoh et al. [14], worked on suitability analysis for the production of rice in Benue state, Nigeria. Ajala et al. [21] studied soil suitability analysis for cassava production in Kwara state, Nigeria. In Rivers state, Ondo, Katsina and Oya states, Peter and Aumwerri [22], Tenkpa and Balogun [23], Abdullahi et al. [24] and Ayaode [25] evaluated agricultural lands for the production of Citrus, Cocoa, Millet and Rice respectively using GIS, AHP or a combination of both. Generally, factors affecting land suitability do not have an identical level of significance. Hence, numerous factors must be taken into account in order to determine if a particular area of land is suitable for agricultural production or not. The weights (influence) of these criteria and the scores of the sub-criteria were calculated using a variety of ways [26].

The objective of the current study was to ascertain the agricultural areas suitable for yam production using AHP and the GIS technique. The AHP technique is one of the multi-criteria decision-making methods that are frequently employed in agricultural land use suitability analyses [26]. Yam production is irregular across Nigeria. An understanding of the areas suitable for yam production would therefore become a vital starting point for addressing the insufficiency of yam production in Nigeria. Previous similar studies conducted (on yam specifically) in Nigeria [4-5,27] either focused on some sections of the country rather than a national spatial scope, and/or did not adopt the use of geo-spatial tools, thereby suggesting a critical knowledge gap that is most likely a major contributory factor in the relatively low yam production levels across Nigeria. This study therefore closes the identified knowledge gap by adopting geospatial tools in analyzing key weather and soil parameters across all sections of Nigeria.

2. Materials and Methods

2.1. Study Area

Nigeria is located between 4° and 14° latitude and 3° and 15° longitude (Figure 1). The Swamp Forest, Tropical Rainforest, Guinea Savannah, Sudan Savannah, and Sahel Savannah are among the vegetation types found on the 923,769 square kilometers of land [28]. The dry and wet seasons are the two basic seasons in Nigeria. A dusty air flux from the Sahara desert known as Harmattan characterizes the dry season, while an air flux from the South Atlantic Ocean characterizes the rainy season [29]. Projected increases in surface temperature, variable precipitation, land and vegetation degradation, rises in sea level and flooding, drought and desertification, increased frequency of severe weather events, changes in fresh water resources, and the loss of biodiversity are all signs that Nigeria's climate system is changing [30-31]. Nigeria has a tropical climate in general, but there are many regions within the country that have different climate conditions. Mangrove forests, swamps, and hot, humid temperatures can be found along the southern ocean coast, particularly along the Niger Delta, resulting in extremely wet conditions. The Niger and Benue river valleys meet in the inland area of Nigeria, which is the country's largest and most expansive area, with a diverse flora.

2.2. Data and Methods

2.2.1. Data

The data records used in this research work include: climate, soil, and environmental datasets. The climate data comprised of precipitation and temperature variables was obtained

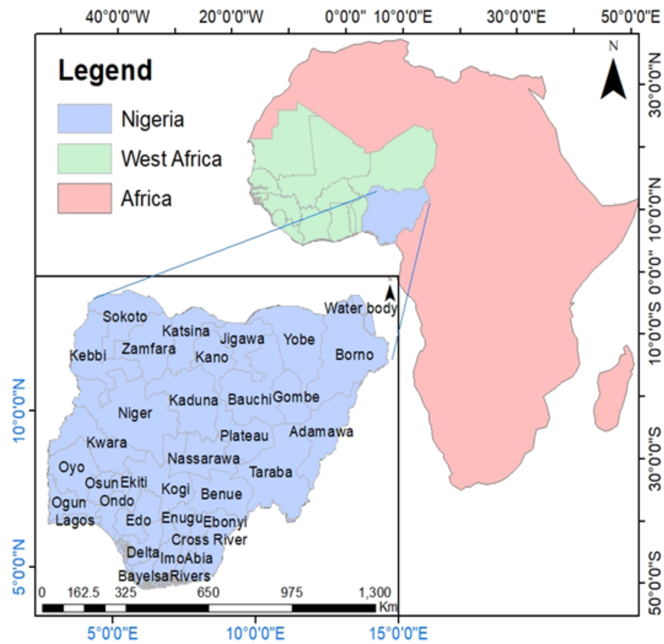

Figure 1. Study Area

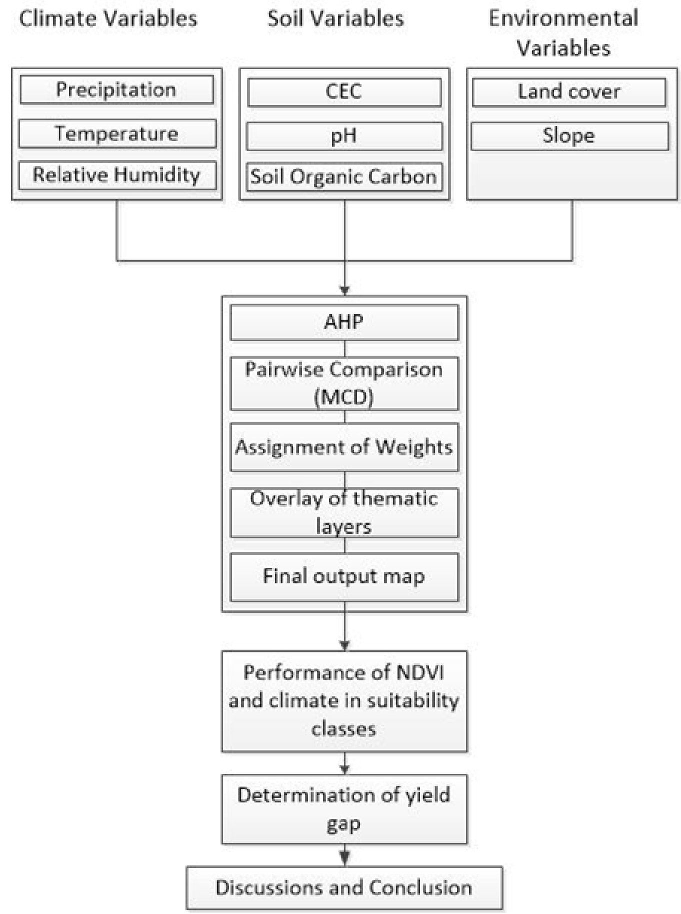

Figure 2. Research Flowchart. CEC refers to Cations exchange Capacity and pH refers to potency of hydrogen

from the Climate Research Unit (CRU), and relative humidity from the European Center for Medium Range Weather Forecast (ECMWF) version 5, Reanalysis data (ERA-5). The soil data set is comprised of pH, cation exchange capacity (CEC), and soil organic carbon (SOC). Land use and land cover data were obtained from the European Space Agency (ESA). The slope data was retrieved from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM). All the various data sources used in this work are shown in Table 1.

2.2.2. *Analytical Hierarchy Process (AHP)*

The AHP method was used to develop a yam suitability map for large scale yam production. The AHP method, documented by Saaty [32], is a Multi-Criteria Decision-making (MCD) technique for resolving complex issues [33-34]. Figure 2 illustrates the procedure used in modeling the suitability of yam production in Nigeria. The steps are (1) identification and assessment of criteria and sub-criteria classes; (2) determination of a Geography Information System (GIS) database with the criteria and sub-criteria, with each criterion's relevance being weighted and obtained using the MCD-AHP technique; (3) determination of the final suitability map for yam production from the weighted overlay process in ArcGIS; and (4) evaluation of vegetation and climate trends in the various suitability classes.

Following the preparation of the thematic layers (steps 1 to 2), the AHP process was used to assign weights to all of the criteria considered in this study. The criteria used in the work are important for yam growth and development. They include temperature, precipitation, relative humidity (Rh), pH, slope, soil organic carbon (SOC), land cover, and cation exchange capacity (CEC) presented in raster format.

Prior to creating the pairwise matrix, reclassification was used to standardize the layers of each sub-criterion. A codification of yam suitability options was then built using thresholds found in related literature, as illustrated in Table 1. The sub criteria were reclassified as "HS", "S", "MS", and "NS", representing Highly Suitable, Suitable, Moderately Suitable, and Not Suitable regions respectively.

The weighting of these influencing factors is based on factors that favor yam growth and expert opinion. A parameter with a high weight indicates a layer that will have a significant impact on yam production and vice versa. The relative importance of the values used for each parameter was assigned based on Saaty's scale of preference (1–9). Additionally, the weights were assigned by reviewing earlier research and field experience. Table 2 provides the Saaty's relative relevance rating [32]. A pairwise wise comparison matrix will be formed which will show the thematic layers' allocated weight and rank. To estimate the weights, the eigenvector method is used to determine the largest eigenvalue [35]. The pairwise comparison matrix (PCM) B of m criteria constructed based on Saaty's scale of importance (Table 2), which is of the order $(m \times m)$, is the basis

Table 1. Parameters, data sources and their suitability classification

Parameter	Data source	Data Range			
		S1	S2	S3	NS
Temp. (^{o}C)	http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.00/data/	20-30	30-34	34-35	<20 >35
Prec. (mm/yr)	http://data.ceda.ac.uk/badc/cru/data/cru_ts/cru_ts_4.00/data/	1000-2000	2000-3500	>3500	
pH	http://dx.doi.org/10.3334/ORNLDAAC/1247	5-7.4	7.4-7.8	5.1-5.6	<5.1 >7.8
Rel. Humidity (%)	http://cds.climate.copernicus.eu	High	Mid	Low	
CEC (cmol/kg)	http://dx.doi.org/10.3334/ORNLDAAC/1247	17-23	10-16	5-10	<5
Land Cover (ESA sentinel)	http://www.esa-landcover-cci.org/	Croplands, Tree Cover	Mosaic Natural Vegetation	Grasslands, Sparse vegetation, shrubs, herbs	Urban, Built, water
Slope (%)	http://srtm.csi.cgiar.org/	0-4	4-8	8-20	>20
SOC (g/kg)	http://dx.doi.org/10.3334/ORNLDAAC/1247	>50	30-50	0-30	

for the factors influencing the weights [36].

$$B = \begin{bmatrix} b^{11} & b^{12} \ldots\ldots\ldots & b^{1m} \\ b^{21} & b^{22} \ldots\ldots\ldots & b^{2m} \\ b^{m1} & b^{m2} \ldots\ldots\ldots & b^{mm} \end{bmatrix} = (b_{ij})_{m\times m} \tag{1}$$

Similarly, $B = \left[b_{ij}\right],\ \ i, j = 1, 2, 3, \ldots\ldots .m;$
In general, the matrix B has the properties of reciprocality and consistency, expressed as

$$b_{ij} = 1/b_{ij}(i \neq j)$$

And

$$b_{ij} = b_{ik}/b_{jk} \text{ for any } i,\ \ j \text{ and } k \tag{2}$$

The weight of all the parameters was obtained using the pairwise comparison matrix and the maximum characteristic root was determined as

$$B^{*}v^{*} = \lambda_{max}v^{*} \tag{3}$$

Where, matrix B^{*} represents the estimate of B [35], v^{*} the priority vector and λ_{max} the Eigen value for B.
The Consistency Ratio (C_R) is a criterion for judging a decision made at random [37]; it is given by

$$C_R = C_I/R_I \tag{4}$$

Where, C_I is the consistency index while R_I is the random consistency index which depends on the order n of the matrix [32]. C_I is given by

$$C_I = \lambda_{max} - 1/m - 1 \tag{5}$$

Table 2. Saaty's Scale of Importance

Variable	Preferences
1	Equal Importance
3	Moderate Importance
5	Strong Importance
7	Very Strong Importance
9	Extreme Importance
2, 4, 6, 8	Intermediate Values between adjacent values

2.2.3. *Validation of Results*

The gridded Advanced Very High Resolution Radiometer (AVHRR) Third Generation Normalized Difference Vegetation Index (NDVI3g) of the Global Inventory Modeling and Mapping Studies (GIMMS) with a temporal resolution of 15 days was utilized for validation of the derived suitability classes [38, 39]. The NDVI spans from +1.0 to -1.0 and in locations with barren rock, sand, or snow (< 0.1), values are often relatively low. Senescent crops and sparse vegetation like shrubs and grasslands (approx. 0.2 to 0.5) might contribute to moderate vegetation. High NDVI values (approx. 0.6 to 0.9) are correlated with dense vegetation, such as that seen in temperate and tropical forests, or with crops in their prime developmental stage [40]. NDVI is given [41] by

$$NDVI = \frac{B_{NIR} - B_{RED}}{B_{NIR} + B_{RED}} \tag{6}$$

Where B_{NIR} and B_{RED} represents the Near-Infrared and Red bands respectively.

2.2.4. *Pearson Correlation Coefficient (r)*

Pearson correlation analysis was employed to ascertain the link between vegetation and climate parameters in the various suitability classes.

$$r = \frac{\sum_{k=1}^{m}\left(y_j - \bar{y}\right)(k_j - \bar{k})}{\sqrt{\sum_{k=1}^{m}(y_j - \bar{y})^2 . \sum_{k=1}^{m}(k_j - \bar{k})^2}} \tag{7}$$

Where y and k are the variables and m refers to the length of the variables.

3. Results and Discussion

3.1. Spatial Distribution of variables

Figure 3 depicts the studied maps of (a) mean temperature (2m) from 1985 to 2015, with values ranging from 20.3 to 31.1° C, (b) Annual mean precipitation, ranging from 286.7 to 2055.4 mm/yr, (c) relative humidity, ranging from 40.7 to 91.2 %, (d) CEC from 0.0 to 85.0 cmol/kg, (e) SOC from 0.0 to 4.2, (f) pH from 4.3 to 8.5, (g) various land cover classes, and (h) slope (% rise) from 0.0 to 45.0. High temperature values are most prevalent in the northern part of the study area. Relative humidity and precipitation, on the other hand, are more widely distributed in the southern part of the research area. The spatial maps of CEC, SOC and pH revealed variable distributions across the study area. The slope map displayed in Figure 3 indicates the highest values around the Mambilla and Jos plateaus, while low values are scattered around the Niger-Benue trough and Niger Delta area. In Figure 4, the examined parameters (Figure 3) are used independently for the evaluation of suitable areas for yam production. Each parameter yields a varying degree of suitability for yam cultivation in Nigeria based on the suitability groups or classes: Highly Suitable (HS), Suitable (S), Moderately Suitable (MS) and Not Suitable (NS).

The yam is a tropical root tuber and vine that is intolerant of cold. Temperatures between 25 and 30°C are required for yam tuber growth, while temperatures below 20°C stifle growth [42, 43]. High temperatures exceeding 35 °C, according to Adifon et al. [44], are detrimental to yam growth and development and may cause fluctuations in moisture content, which may have an influence on agricultural activities if the plants have adaptation problems [15]. The majority of yam varieties require an average of 7 to 9 months of growing time before harvesting. To fully exploit the yam's production potential, it requires over 1,500 mm [42, 43] of annual precipitation distributed evenly over the vegetation period. In contrast, high precipitation amounts in excess of 3500 mm are not too good for yam cultivation and may affect its production. As a result, a long rainy season during the growing season has a positive impact on yam yield, especially if precipitation is well distributed during the wet season with adequate humidity. As a key weather factor that affects the amount of moisture in the atmosphere, humidity has a considerable impact on agricultural output [15]. Seasons and regions in the northern section of the country with abrupt heavy precipitation amounts and distributed within 2 to 3 months may not be favorable for yam production. After the few months of heavy precipitation, the remaining months may be too dry for the yam, except in areas where irrigation measures are put in place. Arguably, the plant can withstand longer periods of drought, but this reduces the yield significantly. In terms of storage, low humidity and dry conditions are necessary for long-term storage to avoid damage to the yields.

Yams also require red loam soils with a pH range of 5.0 to 7.0 [45]. The sandy clay loams are the best soils for growing yams. In Nigeria, yams can be grown in almost any soil type if the ridges are raised properly and stuffed with organic matter. The organic material in the soil enhances the soil structure, works as a steady source of manure, and promotes high yam tuber production. Other critical requirements for yam growth include sufficient drainage, adequate aeration, crumbly soil, adequate moisture supply, and sticks or tiny trees to serve as stacks for the leaves to creep and develop properly without interference.

The gradient (slope) of the research area is very important in determining the pattern of land use, which has a direct impact on groundwater flow in any area [45]. A research work by Poesen [46] reported that as the slope angle increased, so did the rate of infiltration [47]. The slope of an area influences surface water infiltration. In a given region, groundwater infiltration at the surface may not occur at the same gradient. Areas with gentle slopes experience the highest infiltration and minimal amount of surface water runoff, whereas regions with steep slopes may experience high runoff and minimal infiltration of surface water [34].

3.2. Determination of Pairwise Matrix and integration of thematic layers

Using equations 1 to 5 and Table 2, a pairwise comparison of all the thematic layers (rasters) was performed in order to create a PCM. The sub-classes (sub-criteria) of each layer rank were assigned scores from 1 to 9 in relation to their influence on yam production. The pairwise matrix is given in Table 3. The results show that temperature had the highest influence, followed by precipitation and land cover, with weights of 30.9, 24.7, and 15.9, respectively. Each thematic layer and their associated attribute classes were assigned weights and ratings before being integrated (overlayed) in ArcGIS software using the spatial analyst tool box. The final overlayed map is given in Figure 5. During the pairwise comparison matrix via the MCD analysis, the consistency index was obtained as 7.2%, which indicates a fair judgment. The highly suitable (HS) areas are mainly scattered in the south and north-central areas, while the marginally suitable (MS) areas are mostly located in the far north. Arguably, the whole country is suitable (S) for yam production, with most of the pixels scattered across the study area. A few areas that are not suitable (NS) for yam production comprise bare land (open fields), water, and urban areas. Figure 6 shows the percentage composition of landmass for each suitability class. The result indicates that HS, S, MS, and NS areas account for 11.79, 82.68, 4.05, and 1.47% of the study area, respectively. HS areas are primarily found in the north-central and southern regions, while S areas are scattered all over the study area from north to south. Meanwhile, MS areas are majorly observed in the country's extreme north. NS areas are comprised of wetlands, bare areas, open spaces, and urban centers.

Table 3. PCM of all the variables relevant to yam crop suitability in Nigeria

	TEMP	PRE	LCD	CEC	SOC	pH	R.HUM	SLP	WEIGHT
TEMP	1.000	2.000	3.000	5.000	4.000	6.000	5.000	7.000	30.9
PRE	0.500	1.000	3.000	4.000	4.000	5.000	5.000	7.000	24.7
LCD	0.333	0.333	1.000	3.000	3.000	5.000	4.000	6.000	15.9
CEC	0.200	0.250	0.333	1.000	3.000	4.000	3.000	3.000	10.0
SOC	0.250	0.250	0.333	0.333	1.000	4.000	3.000	5.000	8.1
pH	0.167	0.200	0.200	0.250	0.250	1.000	3.000	3.000	4.5
R.HUM	0.200	0.200	0.250	0.333	0.333	0.333	1.000	1.000	3.2
SLP	0.143	0.143	0.167	0.333	0.200	0.333	1.000	1.000	2.7

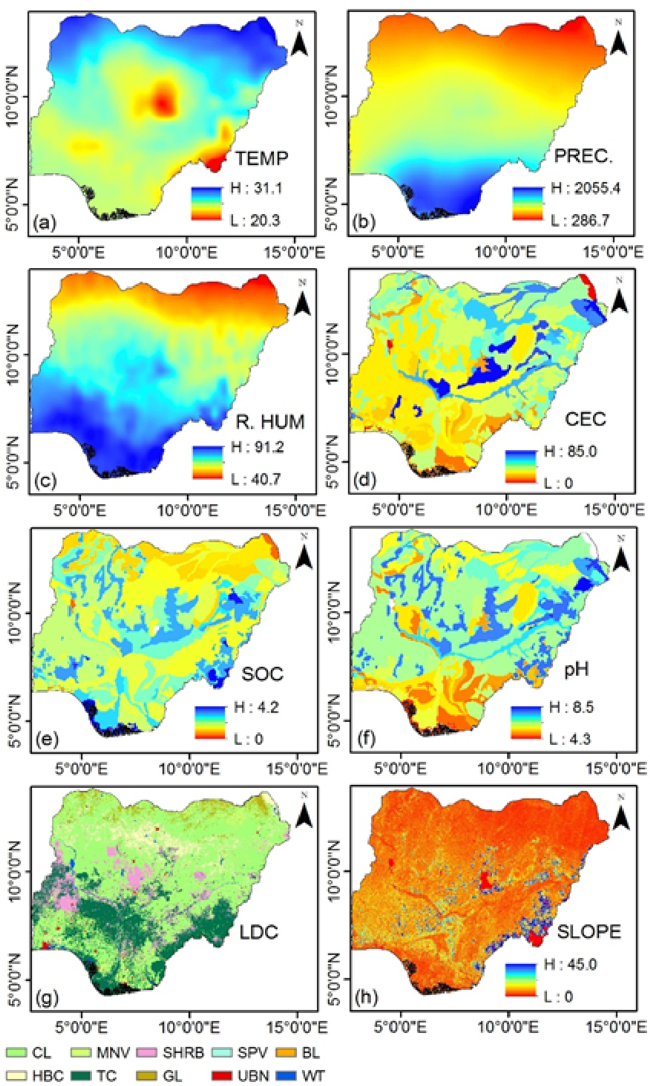

Figure 3. Maps of (**a**) mean temperature (^oC), (**b**) annual mean precipitation (mm), (**c**) relative humidity (%) from 1985-2015. (d) Cations Exchange Capacity (cmol/ kg), (e) Soil Organic Carbon (%) (**f**) Land cover, (**g**) slope (%). CL is for cropland, MNV mosaic natural vegetation, SHRB shrubs, SPV sparse vegetation, BL Bare land, HBC herbaceous, TC tree cover, GL grassland, UBN Urban and WT water

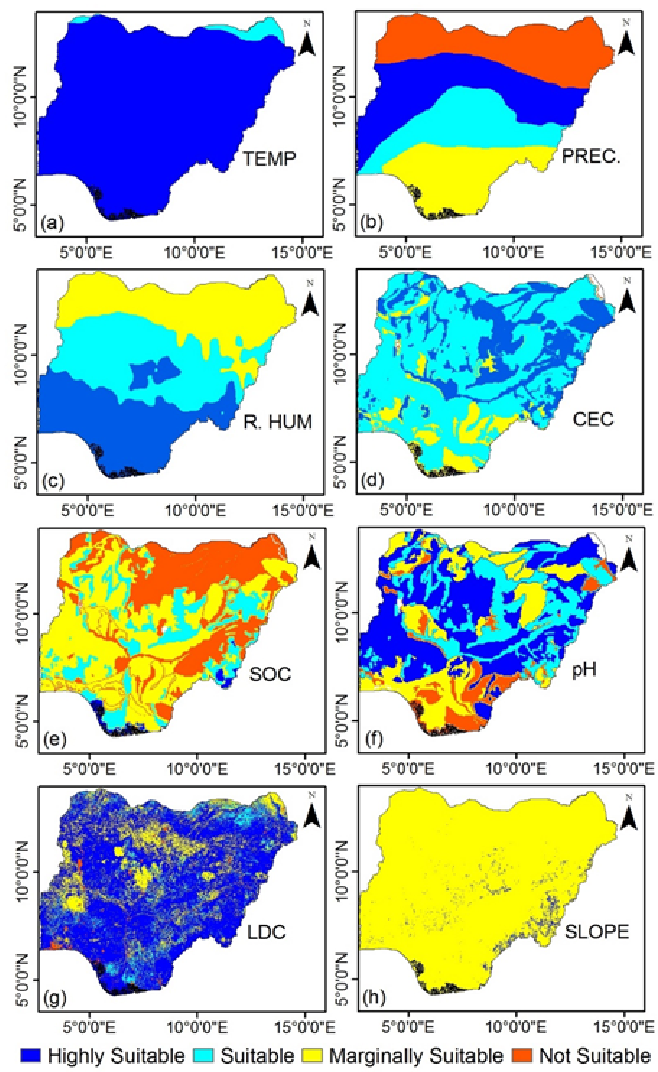

Figure 4. Raster map showing suitability criteria for yam cultivation Nigeria, constraint (**a**) mean temperature, (**b**) mean precipitation, (**c**) relative humidity (d) Cations Exchange Capacity, (e) Soil Organic Carbon, (**f**) Land cover, (**g**) slope

3.3. Relationship between NDVI and Climate parameters in various suitability classes

According to Nwankwo and Ukhurebor [3], monitoring climate variability is crucial because of the functions it plays in the agricultural system. In this work, the interaction between NDVI and climate variables was determined in the various suitability classes in Nigeria. Even though there are many vegetation indices used in studying vegetation activity, NDVI is one of the most extensively used. The NDVI index measures the green-

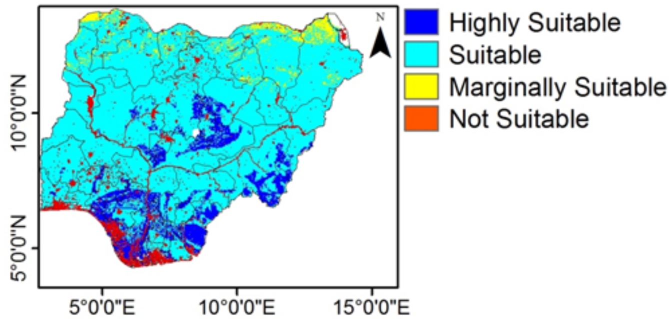

Figure 5. Map of land suitability analysis for yam field cultivation based on multi-criterion decision method

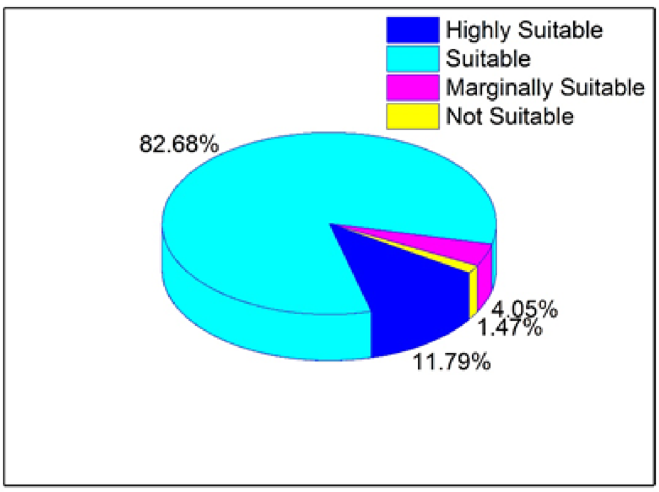

Figure 6. Pie chart showing percentage composition of the suitability classes

ness of vegetation over a given area. It can be used as a proxy for vegetation productivity [41, 48] and phenology [40]. The NDVI across the seasons in HS, S, and MS suitability classes was extracted and presented in Figure 7. The results show that NDVI is above average (>0.5) from Apr to Dec for the HS class, and from Jun to Nov for the S class. In contrast, for the MS class, NDVI is below average (<0.5) for all the months. Similarly, precipitation is > 100 mm/month between April and October for the HS class, between May and September for the S class, and between June and July for the MS class. Temperatures are higher during the start of the season (Apr-May) and lower in Jul-Aug for all classes. NDVI and precipitation are bimodal in HS suitability (Figure 7). In contrast, NDVI and precipitation are unimodal in S and MS. Also, temperatures are bimodal in all the suitability classes, with peaks in the MAM and SON seasons. Meanwhile, NDVI for the HS class has peaks in MAM and SON while a single peak exists in JJA for the S and MS classes. Overall, the NDVI and precipitation range in the HS class is higher, followed by the S class, and then the MS class. In contrast, the temperature range in HS is lower, followed by S class, and then MS class. This shows that there is abundant precipitation in the HS class and temperature remains the limiting climatic variable. In contrast, temperature (precipitation) is normally high (low) in the MS class. Meanwhile, the *S* class has moderate precipitation and temperatures, which are just sufficient for yam production. Our method shows that there was consistency in the MCD analysis during the assignment of weights. Given that temperature and rainfall are directly related to how biologically plants grow, there is a strong association between agricultural productivity and these weather factors [15].

Figure 8, 9, and 10 show the scatterplot matrix of NDVI, precipitation, and temperature for the various suitability classes. The results show that in the HS class (Figure 8), NDVI is positively and significantly correlated with precipitation, r = 0.552 ($p < 0.01$), and NDVI is negatively and significantly correlated with temperature, r = -0.254 ($p < 0.01$). Meanwhile, precipitation correlates negatively and insignificantly with temperature in the HS class, r = -0.429 ($p < 0.01$). In S class (Figure 9), NDVI was positively and significantly correlated with precipitation, r = 0.702 ($p < 0.01$); NDVI was negatively and significantly correlated with temperature, r = -0.161 ($p < 0.01$). Meanwhile, precipitation correlates negatively and insignificantly with temperature in the S class, r = -0.048 ($p = 0.325$). Also, in the MS class (Figure 10), NDVI is positively and significantly correlated with precipitation, r = 0.685 ($p < 0.01$), and NDVI is negatively and significantly correlated with temperature, r = -0.129 ($p < 0.01$). Meanwhile, precipitation correlates positively and insignificantly with temperature in the HS class, r = 0.068 ($p = 0.165$). The NDVI trends in the HS, S, and MS classes are 0.000228, 0.000164, and 0.000037 NDVI/month, respectively. For precipitation, the trends in the HS, S, and MS classes are -0.002459, 0.015347, and 0.0355287 mm/month, respectively. In the HS, S, and MS classes, the temperature trends are 0.000944, 0.001344, and 0.001761 °C/month, respectively. Specifically, NDVI increases with an increase in precipitation at different lags (1 to 2 months) for all the suitability classes. In contrast, NDVI decreases with an increase in temperature for all the suitability classes. The best agreement between NDVI and temperature is at the start (MAM) and end (SON) of the season. The work shows that Nigeria's climate system is primarily influenced by precipitation, followed by temperature, which is in agreement with a report by Igbawua et al. [49].

3.4. Yam Production and Yield Gap in Nigeria

As earlier mentioned, Awoniyi & Omonona [5], Ike & Inoni [6] noted that *Dioscorea rotundata* (white yam) and *Dioscorea alata* (water yam) are the major yam species cultivated in Nigeria. Over the years, Benue, Taraba, Nassarawa, Enugu, Kaduna, Cross River, Ondo, Ekiti, Kogi, and Niger [50]. From Figure 5 and 6, the total area of land in HS, S, and MS available for yam production is 107,059.4474, 746,718.8272, and 33,074.9333 km^2 respectively, which represents 10,705,944.74, 74,671,882.72 and 3,307,493.33 hectares respectively. According to Verter and Bečvářová [7], the yield rate was between 20–50 tons/hectare in years with bumper harvests, while about 10 tons/hectare was in years with poor harvests.

To get the yield gap, we adopted the average yield in years of poor harvest (to account for worst case scenarios) to compute the expected yield in HS, S, and MS. The expected yield for MS, S, and HS using the yield rate of 10 tons/hectare indicates

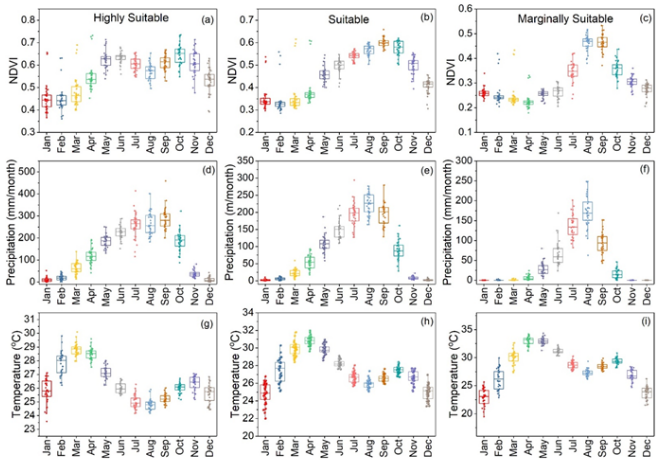

Figure 7. Seasonal NDVI for HS, S and MS suitability classes

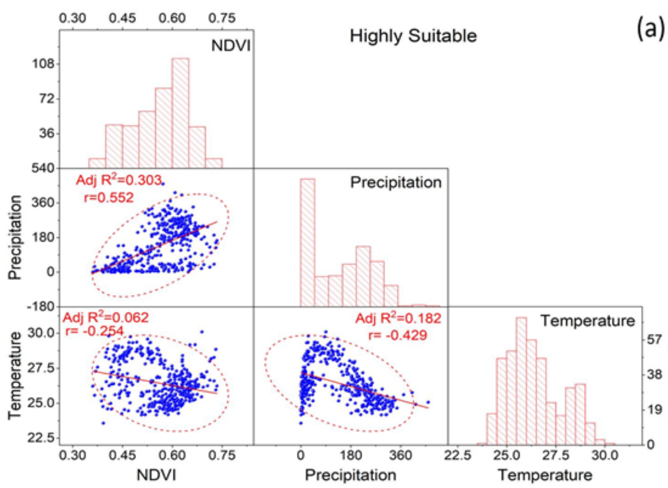

Figure 8. Scatter plot matrix for NDVI and climate parameters for HS region

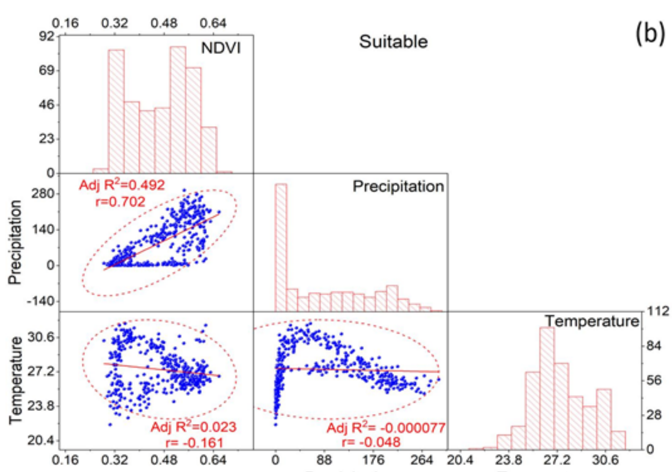

Figure 9. Scatter plot matrix for NDVI and climate parameters for S region

107.06, 746.72, and 33.07 million tons per hectare in the study area. The total area comprising HS, S, and MS is about 886.85

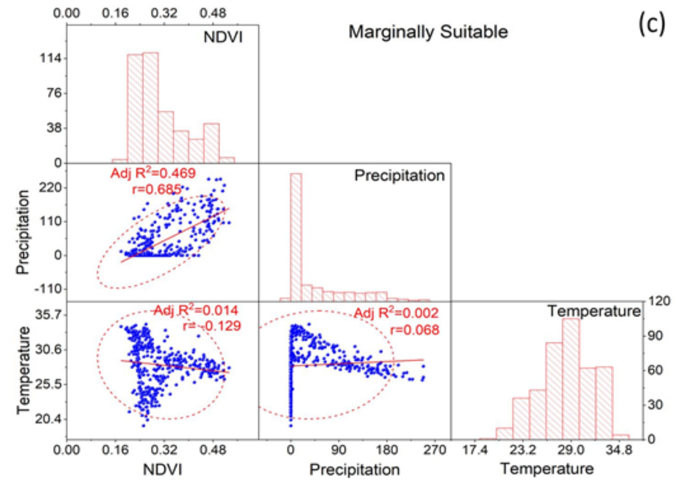

Figure 10. Scatter plot matrix for NDVI and climate parameters for MS region

million tons. The expected yield is far above the actual yield of 38.00 [7] and 50.05 [8] million tons for 2012 and 2019, respectively. The yield gap between the actual and expected yield is more than 800 million tons. In general, the expected yield is not always achieved due to a variety of factors such as declining soil fertility, poor planting methods, high labor costs, increase in pest [51], crop rotation, climate change, floods, droughts, and persistent displacement of farmers from their settlements. This is in addition to other factors such as increasing population, which is driving land fragmentation, and declining soil productivity as a result of shorter fallow periods and prolonged chemical application (synthetic fertilizer and pesticides/herbicides). Also, the expected yield can never be achieved because most of the fertile lands are yet to be ploughed and they are covered by other land cover types.

4. Conclusion

Yam, arguably one of the main food items in homes across Nigeria, is not cultivated all year round. It is heavily dependent and reliant on rain during the wet season and is, therefore, a mono-seasonal crop. A suitability analysis for yam production in Nigeria was done to determine suitable regions for yam cultivation, labeled as highly suitable (HS), suitable (S), marginally suitable (MS) and not suitable (NS). The approach uses both subjective and objective techniques to assign weights to variables through the GIS and AHP methods. The variables were later overlayed into a single suitability map in ArcGis 10.5. Given the high potential of yam production in Nigeria, it is essential to determine the suitable regions for yam production over the study area to improve food security and maximize foreign exchange.

Our findings show that HS, S, MS, and MS were 11.79, 82.68, 4.05, and 1.47 % of the study area. Further analysis showed that vegetation vigor (activity) in the HS regions was higher, followed by S regions, and then MS regions. Similarly, climate variables in HS regions were more favorable for plant growth, followed by S regions and MS regions. This has been confirmed by Pearson correlation analysis between vegetation (NDVI) and climate parameters in the various suitability classes. Our findings also show that there is a high yield gap in yam production over the study area. The yam crop is not the only crop that is produced on the land that is suitable for its production. Thus, yam production is not maximized over the study area. Other factors include crude agricultural practices, multiple cropping, floods, climate change, drought, urbanization, and population increase.

Conclusively, this approach is very useful in land suitability assessment. The methods and materials are very cheap and readily available. The results from this work can serve as a guide for future yield projections in yam production by policymakers and agriculturists. Understanding the lands best suited for yam planting would reduce wastage of resources increase productivity, which will help improve food security. The optimization of yam yield in Nigeria will go a long way in improving local consumption and foreign exchange.

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