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Agricultural Land Suitability Assessment using Fuzzy Logic and Geographic Information System Techniques

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ABSTRACT

Fuzzy logic and Geographical Information System (GIS) based techniques were used for land suitability evaluation and production of land suitability maps for oil palm cultivation in Ife Central Local Government Area of Osun State, Southwestern Nigeria. Land and climatic characteristics data were obtained from a previous soil fertility evaluation of Ife Central Local Government Area. Ten land and climatic characteristics fitted to membership functions were used in computing land suitability index for each point observation based on the Sematic Import (SI) model. Average membership value for cation exchange capacity (CEC) is the lowest (0.216), whereas that of pH is the highest (0.809). Computed land suitability index for oil palm in the study area ranged from 0.32 to 0.52 with a mean of 0.44. CEC, annual rainfall and months of dry season with mean membership functions of 0.21, 0.22 and 0.24 respectively are the major constraints to oil palm cultivation. Land suitability map was produced using G.I.S based techniques. The use of fuzzy logic has proved valuable for identifying major constraints to oil palm cultivation. The production of suitability maps through the use of GIS techniques will further enhance decision making and strategies in overcoming these constraints.

Keywords: Fuzzy Logic, G.I.S, S.I Model, Oil Palm and Land Suitability Map

I. INTRODUCTION

The need for increased production of food crops, eco-friendly practices, and optimal utilization of agricultural land/soil resources has become a major developmental issue in Africa (Panel, 2014, Ademola et.al, 2004). Much attention is now being shifted on selection of a crop which best suits a particular agricultural land area (Ogunlade et.al, 2012).

Crucial to the estimation of land suitability is the matching of land characteristics with the requirement of envisaged land utilization types (Sarmadian et.al, 2014). Unfortunately most of these procedures are highly subjective. It is important to utilize techniques that minimize human bias to improve the pragmatic values of land suitability assessment. This project therefore aims at applying fuzzy logic and GIS based techniques for agricultural land suitability assessment in Ife Central Local Government Area.

The objectives of this project were to (i) apply fuzzy logic to evaluate land suitability for oil palm cultivation in Ife Central Local Government. (ii) production of land suitability map for oil palm cultivation in the study area using GIS techniques.

II. METHODS AND MATERIAL

A. Study Area

The study area covers Ife Central Local Government Area located in Osun State, South-western Nigeria. It lies between latitudes 7o 28' 43.5''N and 7o37' 51.41''N and spans between longitude 4o 27' 22.5''E and 4o35' 40.61''E. Figure 1, illustrates the map of the study area. The climate of the study area can be described as humid tropical. The geology of the area as reviewed by (Rahaman, 1976) includes granite gneiss and schist epidiorite. The soil of the study area is Alfisols with Ferruginous Tropical overlay in most cases. The soil belongs to Iwo association at series level and can be classified as OxicTropudalf by the USDA system. They are principally derived from granite and gneiss parent materials. The area is drained by a very large network of rivers such as Obudu, Opa, Esinmirin, Ominrin, Ogbe, Okun, Mokuro and other smaller tributaries (Maruf et al., 2015).

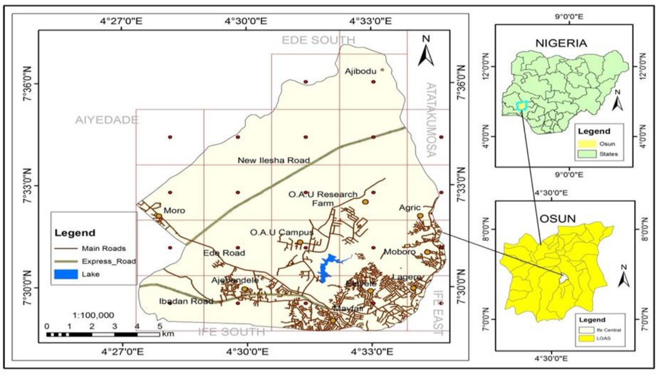

Figure 1: Map of the study area

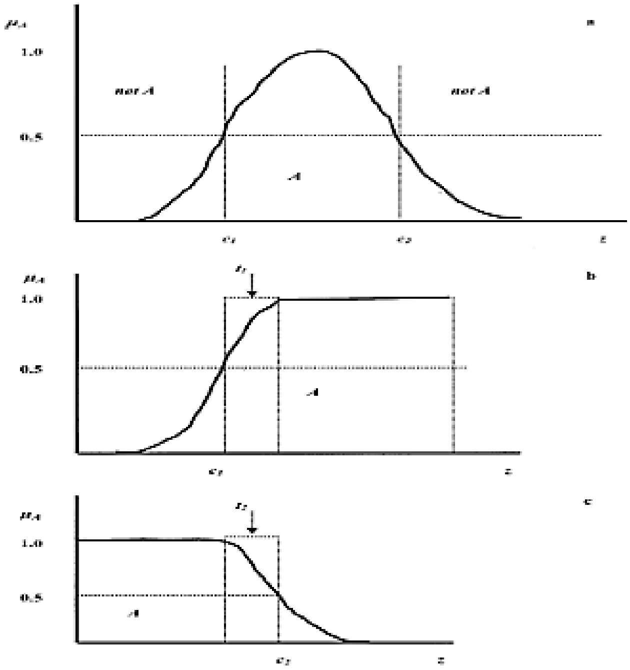

Figure 2: Different membership functions and parameters used to determine membership values of land characteristics (Burrough and McDonnell 2000).

B. Data Sources

Land characteristics data were obtained from a soil fertility evaluation of Ife Central Local Government Area by Alabi et al., (2012). Ten land characteristics in five (5) land quality groups considered important for oil palm cultivation were selected. Descriptive statistics for the dataset are presented in Table 1.

TABLE 1
DESCRIPTIVE STATISTICS FOR LAND CHARACTERISTICS

Land characteristics	**Minimum**	**Mean**	**Maximum**
Climate			
Annual rainfall (mm)	1150	1250	1350
Month of dry season	4	4	4
Relative humidity (%)	41.8	73.9	75.9
Topography			
Slope (%)	2	7	14
Wetness			
Drainage	1	1.4	2
Soil physical characteristics			
Clay (%)	5.4	27.29	61.81
Sand (%)	34.12	56.81	77.2
Fertility			
CEC (cmol/kg)	0.63	3.22	6.13
Organic carbon (%)	0.08	0.93	1.98
pH	5.5	6.43	7.4

C. Fuzzy Logic

Fuzzy sets provide means to model the uncertainty associated with vagueness, imprecision, and lack of information regarding a problem or data (Sivanandam and Deepa, 2007). In this study, fuzzy logic was used for computing land suitability index. Further applications of fuzzy logic include water quality model development (Md et al., 2009), forecasting (Amit and Babita, 2012), land suitability and evaluation (Braimoh et al., 2004; Fang et al., 2014). A fuzzy set may be used for classification of objects where classes do not have rigidly defined boundaries (Zadeh 1965). If Z represents a space of objects or phenomena, then the fuzzy set A is the set of ordered pairs represented mathematically as

$$A = \{z, \mu_A(z)\}, \ \forall \quad z \in Z \tag{1}$$

Where $\mu_A\ (z)$ is the membership function of any $z\ \in Z$ to A by taking values within the interval [0,1], with 0 representing nonmembership and 1 representing full membership of the set (Burrough and McDonnell, 2000). Intermediate values $(0 < \mu_A < 1\ )$ reflect the degree of closeness of an entity to the defined class.

Land suitability evaluation using fuzzy logic consists of three steps

i. Generation of membership values for the land characteristics
ii. Determination of weights for the membership values
iii. Combination of weighed membership values to produce a joint membership value or land suitability index, I.

D. **Membership Values for the Land Characteristics**

There are two main techniques of deriving membership functions for fuzzy sets (Burrough 1989). These are the Similarity Relation model (SR) and the Semantic Import Model (SI). In the SR model the value of the membership function is a function of the classifier used (Ogunlade et al., 2012). SI on the other hand uses a priori membership function to assign individual land characteristics into a membership grade. SI is particularly useful in situations where the users have an expert knowledge of how to group land requirements for a specific use. As such, SI model was used in this study. The basic SI model is of the form

$$\mu_A(z) = \frac{1}{1+\ a(z-c)^2}\ \ for\ 0\ \leq z\ \leq\ \alpha \qquad (2)$$

where A is the land characteristic set; a is the parameter that determines the shape of the function, c (also called the ideal point or standard index) is the value of the property z at the centre of the set and α is the maximum value that z can take. The lower crossover point (LCP) and the upper crossover point (UCP), corresponds to $c_1\ and\ c_2$ respectively in Figure 3a representing situations where the value of the land characteristics is marginal for a specified purpose. At these points, $\mu_A(z)$ = 0.5. For example, for land characteristic clay, the %clay should not be less than 15% (LCP) and should not be more than 35% (UCP). Hence equation 2 was used for clay and sand. If only the lower or upper limits of a class are of practical relevance to the envisaged land utilization type, asymmetric variants of the SI model are used. For instance organic C, CEC and relative humidity in which higher values contributes positively to crop yield, a suitable model is

$$\mu_A(z) = \frac{1}{1+\ (z-c-t_1)^2}\ \ for\ 0 < z\ < c + t_1 \qquad (3)$$

Where t_1 is the width of the transition zone (Figure 3b). The transition zone for an asymmetric model refers to the absolute difference between the value of the property at the ideal and crossover points.

Where lower values of land characteristic contribute positively to crop yield, a suitable model is

$$\mu_A(z) = \frac{1}{1+\{(z-c+t_1)/t_2\}^2}\ \ for\ 0\ < z\ < c - t_2 \quad (4)$$

where t_2 is the width of the transition zone (Figure 3c).

If a range of values are of practical relevance to the envisaged land utilization type, a variant of the SI model is used. For instance for the land characteristic, annual rainfall in which any value from 1600-2000mm is " ideal " for oil palm, a suitable model is

$$\mu_A(z) = 1\ \ for\ t_3 + r_1 \quad \leq z \leq r_2 - t_4 \qquad (5)$$

where t_3 is the width of the transition zone below the lower boundary of the range, r_1 the lower boundary of the range, t_4 the width of the transition zone above the upper boundary of the range and r_2 the upper boundary of the range. For other values of z , equation 3 applies for $z\ < r_1$, whereas equation 4 applies for $z\ > r_1$.

Summarily, equation 1 is the generalized fuzzy set equation while equation 2 is used where a minimum and maximum value of land characteristics is marginal for crop yield (e.g. clay and sand). Equation 3 is used where higher values of the land characteristics contribute positively to crop yield for instance, organic carbon, CEC and relative humidity. Equation 4 is used where lower values of land characteristics contribute positively to crop yield, for instance months of dry season. Equation 5 is normally used where range values of land characteristics contribute positively to crop yield, for instance a pH range of 5.5-6.5 is ideal for oil palm.

Membership functions for land characteristics used in this study were adapted from Sys (1985) and are presented in table 2.

TABLE 2
LAND CHARACTERISTICS AND MEMBERSHIP FUNCTION PARAMETERS

Land characteristics	Model type	Membership function parameters					
		LCP	c	UCP	a	t_1	t_2
Climate							
Annual rainfall (mm)	Asymmetric-Equation (3)	1200	1600-2000	3200	-	400	-1200
Month of dry season	Asymmetric-Equation (4)	-	1	4	-	-	3
Relative humidity (%)	Asymmetric-Equation (3)	60	75	-	-	15	-
Soil physical characteristics							
Clay (%)	Symmetric-Equation (2)	15	25	35	0.01	-	-
Sand (%)	Symmetric-Equation (2)	20	40	60	0.0005	-	-
Fertility							
CEC (cmol/kg)	Asymmetric-Equation (3)	2	16	-	-	14	-
Organic carbon (%)	Asymmetric-Equation (3)	0.8	1.5	-		0.7	-
pH	Asymmetric-Equation (3)		5.5	-	-	1	-

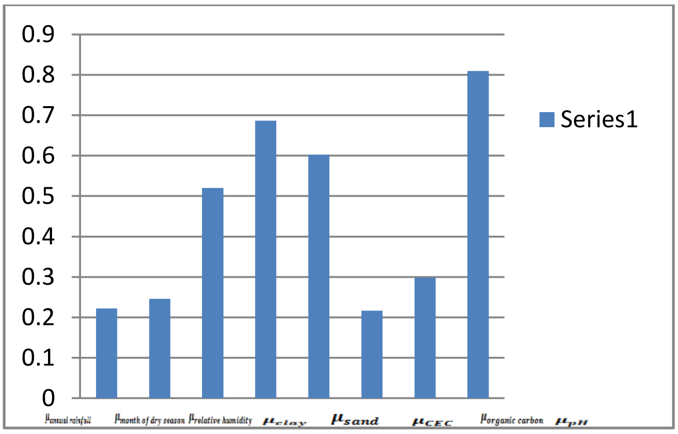

Figure 3: Bar chart representing the membership functions of the land characteristics

E. Determination of weights for the membership values

The choice of weights w_i is crucial in the determination of the overall land suitability index. Choice of weight should be based on data and knowledge of the relative importance of differentiating land characteristics to crop growth (Davidson, 1994, Adzemi et al., 2013).

Simple ranking was used to rate land characteristics from 1 (least importance) to 4 (most important). This ranking was based on literature (Sys 1985, Fugger 1999, Adzemi et al, 2013), expert opinion and their importance to oil palm production.

To ensure that weights sum up to unity, the rank r_i of land characteristics A_i was converted to weight w_i using equation 6

$$w_i = \frac{r_i}{\sum_{i=1}^{n} r_i} \quad (6)$$

The ranking, weights and justification are summarized in table 3

TABLE 3
RANKING, WEIGHTS AND JUSTIFICATION USED IN THIS STUDY

Land characteristics	Rank	Weights	Justification
Climate	4		Climate, especially amount of rainfall is very critical to oil palm production as the cropping system is rain fed.
Annual rainfall (mm)		0.16	
Month of dry season		0.16	
Relative humidity (%)		0.16	
Soil physical characteristics	3		Clay content has a high positive correlation with chemical fertility. Appropriate proportion of soil particles prevents flooding as texture is important for water retention.
Clay (%)		0.15	
Sand (%)		0.10	
Fertility	2		CEC determines the nutrient holding capacity of the soil.
CEC (cmol/kg)		0.09	Soil organic matter is crucial to the supply of N and cations.
Organic carbon (%)		0.09	Nutrient availability in the soil is strongly dependent on pH (Braimoh and Vlek, 2004)
pH		0.09	

F. Land suitability index (I)

The overall land suitability index (I) at each sampling point is computed using the convex combination rule, which is a linear weighted combination of membership values of each characteristic A_i as illustrated in equation 7

$$I = \sum_{i=1}^{n} \omega_i \mu_{A_i} \qquad (7)$$

Where ω_i are the weights of the memberships values μ_{A_i} .

III. RESULT AND DISCUSSION

Statistics of membership values and land suitability index are presented in Table 4. The membership value indicates the degree of suitability at a given location with respect to land and climatic characteristic. For example, membership value of clay (μ clay) is approximately 0.69 thus indicating that suitability of the location is 69% of the ideal requirement of clay for oil palm cultivation. It also implies that averagely the study area has a limitation of 31% with respect to the ideal clay requirement for oil palm cultivation.

Average membership value for CEC is the lowest (0.216), whereas that of pH is the highest (0.809). The suitability index of the study area ranges from 0.32 to 0.52, with a mean of 0.44. Figure 3 is a bar chart illustrating the membership function of the various land characteristics.

TABLE 4
DESCRIPTIVE STATISTICS OF MEMBERSHIP VALUES (M) AND LAND SUITABILITY INDEX FOR OIL PALM.

Land characteristics	Minimum	Mean	Maximum
Climate			
$\mu_{annual\ rainfall}$	0.1813	0.22215	0.2747
$\mu_{month\ of\ dry\ season}$	0.2462	0.2462	0.2462
$\mu_{relative\ humidity}$	0.5204	0.5204	0.5204
Soil physical characteristics			
μ_{clay}	0.0687	0.68676	1
μ_{sand}	0.2242	0.602205	0.9204
Fertility			
μ_{CEC}	0.1852	0.216265	0.2559
$\mu_{organic\ carbon}$	0.0981	0.2979	0.9101
μ_{pH}	0.5	0.80912	0.9901
Suitability Index (*I*)			
$I = \sum_{i=1}^{n} \omega_i \mu_{A_i}$	0.3229	0.44054	0.5217

The limitation of land and climatic characteristics for oil palm production in the study area is in the order of CEC, annual rainfall, months of dry season, organic carbon, relative humidity, sand, clay, and pH.

Land suitability classification in agreement with FAO framework of land evaluation (FAO, 1976) was used in produce the land suitability map in figure 4. The classification used is as follows:

Figure 4: Land suitability classes/road network for the study area

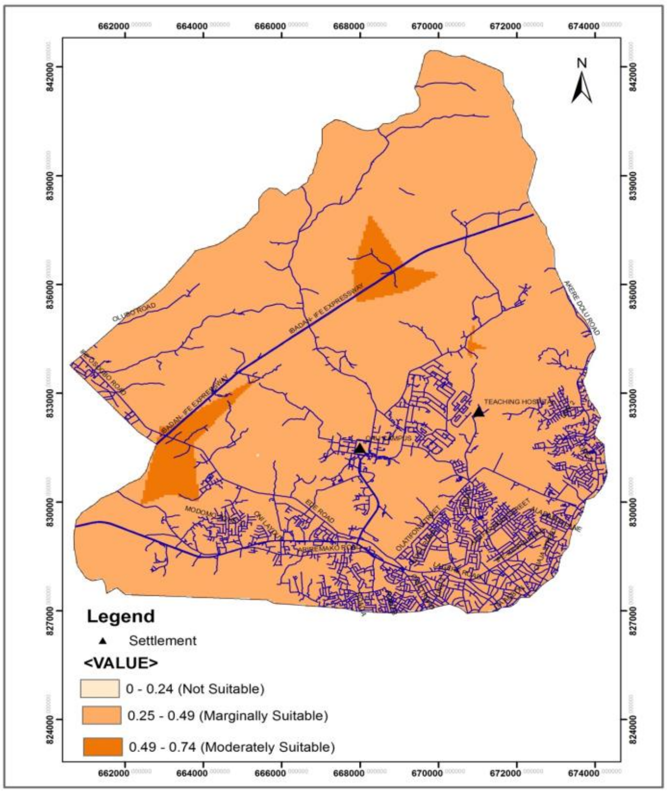

Figure 4 : Land suitability classes/road network for the study area

Class S1 (highly suitable): Land units with no or only slight limitations which in combination give land index values ranging from 0.75 to 1.

Class S2 (moderately suitable): Land units with slight or moderate limitations which in combination give land index values ranging from 0.50 to 0.74.

Class S3 (marginally suitable): Land units with moderate limitations or normally not more than two severe limitations which in combination give land index values ranging from 0.25 to 0.49.

Order N (not suitable): Total area (sq km) of each of the classes is shown in Table 5. It can be observed from Figure 4 that oil palm cultivation in the study area can be classified into moderately suitable and marginal suitable based on FAO frame work of land classification.

TABLE 5
DISTRIBUTION OF SUITABILITY CLASSES (FAO) IN SQ KM.

Class	Area (sq km)	% of Total
Highly Suitable	0	0
Moderately Suitable	5.758	4.12
Marginally Suitable	134.095	95.88
Not Suitable	0	0

IV. CONCLUSION

The use of fuzzy logic and GIS techniques in this study produced land suitability maps for oil palm cultivation in Ife Central Local Government Area of Osun State. Through the use of fuzzy logic, limitations of land and climatic characteristic to oil palm cultivation in the study area were evaluated. Major constraints to oil palm cultivation in the study area are in the order of CEC, annual rainfall, months of dry season, organic carbon, relative humidity, sand, clay, and pH. It is recommended that soil management techniques that will increase the CEC of the soil and also enhance the water holding capacity of the soil especially during the dry season should be adopted to enhance oil palm yield. Also the organic carbon content of the soil should be improved on. The use of fuzzy logic for land suitability evaluation has proved valuable for identifying major constraints to oil palm cultivation. The production of suitability maps through the use of GIS techniques will further enhance decision making and strategies in overcoming these constraints.

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