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LAND SUITABILITY EVALUATION FOR COCOA PRODUCTION IN NIGERIA USING FUZZY METHODOLOGY

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ABSTRACT

Ogunlade MO, Aikpokpodion PO, Braimoh AK (2012) Land suitability evaluation for cocoa production in Nigeria using fuzzy methodology. *Int. J. Sustain. Crop Prod.* 7(3), 13-20.

This study applies fuzzy set techniques to evaluate soils for cocoa in Nigeria. Soil samples were collected across cocoa growing ecologies extending from Southwestern to Southeastern Nigeria. Ten land characteristics fitted to membership functions combined to a land suitability index on the interval [0, 1] using the Semantic Import (SI) model. Land suitability for cocoa ranged from 0.53 to 0.78 with a mean of 0.68. CEC, sand content, and months of dry season with median membership values of 0.38, 0.41 and 0.64 respectively are the main constraints for cocoa production in the study area. Relationship between cocoa yield and land suitability index $(R^2 = 0.65)$ suggests that yield declines at the rate of 16 kg ha^{-1} for every 1% decline in land suitability index. We discuss strategies for ameliorating the identified constraints for sustainable cocoa production.

Key words: *fuzzy set, membership values, land suitability evaluation, Semantic Import (SI) model, cocoa, Nigeria*

INTRODUCTION

Before the discovery of petroleum in 1956, agriculture of which cocoa (*Theobroma cacao)* production was a major part constituted the mainstay of the Nigerian economy. Since the 1970s when petroleum became the major foreign exchange earner for the country, Nigeria had lost its position as one of the leading cocoa exporters, and cocoa production has not kept pace with export market demand. Cocoa export declined from over 200,000 t in mid-1980s to about 170,000 t in the late 1990s (http://faostat.fao.org). More than 70% of Nigerian cocoa farmers are smallholders with average farm size less than 1.5 ha, and most of the increase in yield is due to expansion of land area devoted to cocoa. Cocoa yields are principally affected by soil and climatic variables (Wood and Lass, 1985; Alvim 1993; Hartemink 2003; Hartemink 2005). As such, cocoa cultivation is restricted to southwestern and eastern parts of Nigeria where the annual rainfall is above 1200mm. Much as cocoa is vital for Nigeria's economy, there is currently the lack of a land evaluation system that provides information on the potential of land resources of different areas for the crop. Rather, scientists and farmers resort to terms such as "ideal cocoa soils," "ideal cocoa climate" and "marginal cocoa climate" in describing the suitability of various areas within cocoa agroecosystems in Nigeria. This deficiency hampers exchange of soil/land-use information and agrotechnology transfer. It also leads to duplication of research efforts within the cocoa agroecosystems in the country. In order to circumvent this vagueness in land evaluation, fuzzy set method which is a quantitative approach that estimate the suitability of land on a continuous scale (e.g 0-1), rather than the grouping of land unit into discrete capability units is explored in this study. Fuzzy logic allows an overlap of classes in the attribute space. It enables different land characteristics that determine land suitability to be assessed in concert, rather than individually by separate rules (Van Ranst *et al*. 1996). Fuzzy techniques are flexible in that they capture the continuous variation of soil properties and help to deal with vagueness and imprecision associated with natural resource data (Burrough 1989; Braimoh *et al*. 2004; Samranpong *et al*. 2009). Therefore the objectives of this study were to (i) apply fuzzy techniques to evaluate land suitability for cocoa production in the study area, (ii) assess the degree of limitation posed by land characteristics to cocoa at different sites (iii) generate a yield map that can be used for land use planning and other decisions and (iv) highlight the agronomic management techniques needed to address the soil and climatic constraints to be determined in the study area.

MATERIALS AND METHODS

Study Area and Data Sources

This study covers the major cocoa producing area of Southwestern and Southeastern parts of Nigeria. It lies between Latitude 5^o 32' to 7^o 47'N and stretches between Longitude 3^o 55' to 8^o 42'E (Fig. 1). The Southwestern part is underlain by metamorphic rocks of the basement complex, the great majority of which are of Pre-Cambrian age (Smyth and Montgomery, 1962). The soils are mainly classified as *Typic Kanhaplustalf* and *Typic Haplustalf*. The soils of the study Southeastern part are principally derived from basalt under humid tropical forest vegetation (Eshett 1987). The soils are predominantly classified as *Typic Tropohumult* (Soil Survey Staff 2006).

Fig.1. Map of Nigeria showing the study area enclosed in dashed lines

Land characteristics data were obtained from a soil fertility evaluation of cocoa growing ecologies by Ogunlade and Aikpokpodion, 2006, 2010. The survey covered 26 cocoa plantations across the cocoa growing ecologies. Ten land characteristics in 5 land quality groups considered important for cocoa were selected for the land suitability evaluation. Summary statistics for the dataset are presented in Table 1.

Table 1. Descriptive Statistics for Land characteristics

Land characteristics	Minimum	Mean	Maximum	CV (%)
Fertility				
CEC cmol/kg	6.68	16.65	28.37	39
K mole fraction (%)	0.25	1.10	2.94	23
Ca mole fraction (%)	33.4	69.9	84.6	16
Mg mole fraction (%)	15.4	69.9	66.6	38
Organic Carbon (%)	0.88	1.64	2.99	34
pH	4.7	5.6	6.2	8
Texture				
Sand (%)	16	49	80	5
Clay (%)	10	31	68	6
Climate				
Annual rainfall (mm)	1271	1787	2320	23
Months of dry season	3	3.81	5	21
Relative Humidity (%)	65	72	80	7
Topography				
Slope (%)	2	9.8	20	63
Wetness				
Drainage	1	1.15	2	32

Fuzzy sets for land evaluation

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

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

where μ_A is the membership function. It indicates the degree of membership of *z* in *A* by taking values within the interval [0, 1], with 0 representing non-membership, and 1 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. The Boolean logic on the other hand has two crisp possibilities of membership: none (μ_A = 0) and full (μ_A = 1).

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). SR is analogous to that taken by cluster analysis and numerical taxonomy in that the value of the membership function is a function of the classifier used. SI on the other hand uses a priori membership function to assign individual land characteristic 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, the SI model was used in this study. The basic symmetric SI model is of the form

$$\mu_A(z) = \frac{1}{(1 + a(z-c)^2)} \quad \text{for } 0 \le z \le \alpha \tag{2}$$

where *A* is the land characteristic set, *a* is the parameter that determines the shape of the function and *c* (also called the *ideal point or standard index*) is the value of the property *z* at the center of the set, and α is the maximum value that *z* can take. The lower crossover point (LCP) and the upper crossover point (UCP) represent situations where the value of the land characteristics is marginal for a specified purpose. At these points, $\mu_A(z)$ = 0.5. For instance, for the 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, for the land characteristic “organic C”, CEC and relative humidity in which higher values contributes positively to crop yield, a suitable model is

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

where t_1 is the width of the transition zone. The transition zone for an asymmetric model refers to the absolute difference between the value of the property at the ideal and cross over points.

A similar model [equation 4)] applies to a land characteristic for which lower values contribute positively to crop yield: For instance lower values of drainage, slope and months of dry season contribute positively to cocoa yield hence equation 4 below is appropriate for these land characteristics.

$$\mu_A(z) = \frac{1}{(1 + \{(z - c + t_2)/t_2\}^2)} \qquad \text{for } z > c - t_2 \tag{4}$$

where t_2 is the width of the transition zone.

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 cocoa, a suitable model is

$$\mu_A(z) = 1 \text{ for } t_3 + r_1 \le z \le r_2 - t_4 \tag{5}$$

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 $z > r_2$

Summarily, equation 1 is the generalized fuzzy set equation while equation 2 is used where a minimum and maximum value of land characteristic is marginal for crop yield (e.g. clay and sand). Equation 3 is used where higher values of the land characteristic contribute positively to crop yield, for instance, organic carbon, CEC and relative humidity while equation 4 is used where lower values of land characteristic contribute positively to crop yield, for instance, months of dry season, drainage and slope. Equation 5 is normally used where range values of land characteristic contribute positively to crop yield, for instance a pH range of 5.5–6.5 is ideal for cocoa. Membership functions for land characteristics used in the study 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
CEC (cmol/kg)	Asymmetric1-Equation (3)	2	16	-	-	14	-
Organic Carbon (%)	Asymmetric1-Equation (3)	0.8	1.5	-	-	0.7	-
Relative humidity (%)	Asymmetric1-Equation (3)	60	75	-	-	15	-
Slope (%)	Asymmetric2- Equation (4)	-	2	12.5	-	-	10.5
Drainage	Asymmeric2- Equation (4)	-	1	3	-	-	2
Months of dry season	Asymmetric2-Equation (4)	-	1	5	-	-	4
Clay (%)	Symmetric-equation (2)	15	25	35	0.01	-	-
Sand (%)	Symmetric-Equations	20	40	60	0.0025	-	-
Annual rainfall (mm)	Range Equations (3) – (5)	1200	1600-2000	3200	-	400	1200
pH	Range Equations (3) – (5)	4.5	5.5-6.5	8.0	-	1	na

na = not applicable as the study area; pH ranges from 4.7 to 6.2

Drainage as an ordinal variable was measured as 1- well drained, 2- moderately drained, 3– imperfectly drained, 4- poorly drained and 5- very poorly drained.

The overall land suitability index of cocoa, S is derived from

$$S = \sum_{i=1}^{n} \omega_i \mu_{A_i} \qquad (6)$$

where ω_i are the weights of the membership values μ_{A_i}. The choice of weights ω_i took place in four steps (Table 3). In the first step, the ten land characteristics were grouped into five land quality groups of climate, soil physical characteristics, soil chemical fertility, topography and wetness. In the second step, each group was assigned a rank ranging from 1-4 depending on their importance to cocoa production (Sys 1985; Fasina *et al.* 2007). In the third step, weights for each land quality group was determined using

$$\omega_i = \frac{g_i}{\sum_{i=1}^{n} g_i} \qquad (7)$$

where g_i is the ranking for land quality group i. Lastly, each land characteristic within a land quality group was assigned a weight l_i such that

$$g_i = \sum_{i}^{n} l_i \qquad (8)$$

where n is the number of land characteristics in a land quality group. The ranking and weights and justification are summarized in Table 3.

In summary, equations 6-9 showed how weights were assigned to land characteristics. For instance, in the climate land quality group which was ranked 4th, 0.12 assigned to each of annual rainfall, month of dry season and relative humidity was derived by dividing 4(the rank assigned to climate) by 11(sum of the rank for the five quality groups) and divide the answer by 3(number of land characteristics- (i)annual rainfall, (ii) months of dry season and (iii) relative humidity that make up the climate group) in this study. Similar approach was used to derive the weights of other land characteristics.

Table 3. Ranking and assignment of weights to land characteristics

Land characteristics	Rank	Weights	Justification
Climate:	4		Climate, especially amount and distribution of rainfall are very critical to cocoa production as the cropping system is rain-fed. If the soil physical and chemical properties are suitable and rainfall is not adequate, cocoa production will be grossly affected. The importance of rainfall explains why the growing of cocoa is limited to the southern portion of Nigeria
Annual Rainfall		0.12	
Months of dry season		0.12	
Relative Humidity		0.12	
Texture:	3		Cocoa, being a permanent crop remains on the field all the year round. Texture is very important for water retention during the dry season. Appropriate proportion of soil particles prevents flooding during the wet season. Clay content also tend to have a high positive correlation with chemical fertility.
Clay		0.16	
Sand		0.11	
Fertility:	2		When rainfall and texture of the soil are adequate, next is the fertility status of the soil. ECEC determines the nutrient holding capacity of the soil. Nutrient availability is strongly dependent on pH of the soil. For instance, considerable low pH of less than 3 leads to micronutrient toxicity. However, the average pH of 5.6 in the study area is not a constraint to cocoa production.
ECEC		0.06	
Organic Carbon		0.06	
pH		0.06	
Topography:	1		Slope gradient to a large extent determines the intensity of soil erosion and runoff. Higher percent slope means colossal soil nutrient loss.
Slope		0.09	
Wetness:	1		Drainage influences air and water regime in the soil. In the study area, drainage poses very little limitation to cocoa production.
Drainage		0.09	

For a land evaluation to be useful for land use planning and decision making, it must be able to predict crop yields as well as assess limitations to envisaged use (Johnson and Cramb, 1996; FAO 2007). Hence, for validation we related observed cocoa yields (collected while collecting soil samples for soil fertility evaluation) with land suitability index using

$$Y = a + bX \tag{9}$$

where *Y* is cocoa yield, *X* the estimated land suitability index, *b* the slope and *a* the intercept of the regression line.

RESULTS AND DISCUSSION

Membership values indicate the degree of suitability of land characteristics to cocoa. Table 4 shows that the average membership value of Cation exchange capacity (CEC) is the lowest (0.39), whereas that of pH (0.95) is the highest. Membership value of clay is the most variable with coefficient of variation (CV) of 65%, whereas that of pH is the least variable (CV = 10%). Of the three climatic factors considered, relative humidity has the highest (0.91) mean membership value, whereas months of dry season has the least (0.68). The mean membership values of slope gradient and drainage were 0.62 and 0.89 respectively. The suitability index of the study area (Table 4) ranges from 0.53 to 0.78, with a mean of 0.68 and a coefficient of variation of 9%.

Table 4. Descriptive statistics of membership values of land characteristics and land suitability index for cocoa

Land characteristics	Minimum	First Quartile	Median	Third Quartile	Maximum	Mean	CV (%)
ECEC	0.24	0.33	0.38	0.45	0.63	0.39	25
Organic Carbon	0.56	0.86	1.00	1.00	1.00	0.91	15
pH	0.61	0.96	1.00	1.00	1.00	0.95	10
Sand	0.20	0.32	0.41	0.50	0.96	0.44	42
Clay	0.05	0.16	0.45	0.77	0.99	0.47	65
Annual rainfall	0.62	0.65	0.73	0.87	0.96	0.76	15
Months of dry season	0.50	0.64	0.64	0.80	0.80	0.68	18
Relative Humidity	0.69	0.90	0.93	1.00	1.00	0.91	13
Slope	0.25	0.50	0.50	1.00	1.00	0.62	49
Drainage	0.31	1.00	1.00	1.00	1.00	0.89	29
Suitability Index	0.53	0.65	0.68	0.71	0.78	0.68	9

Hint:First quartile implies 25% of soils have the indicated membership values, median implies 50% of soils have the indicated membership values and third quartile means 75% of soils have the indicated membership values of a given land characteristic

Percentiles of membership values (Table 4) indicate the degree of limitation of each land characteristic for cocoa. The median membership value of ECEC is 0.38, implying that the ECEC suitability of 50% of the study area is 38% or less of the ideal requirement. In other words, 50% of the study area has a limitation of 72% with respect to ECEC. The 75th percentile indicates that the ECEC suitability of three-quarters of the study area is only 45% of the ideal requirement. At most, the ECEC suitability of any location in the study area is 63%. Close examination of Table 4 indicates that within the chemical fertility land quality group, land characteristics limitation is in the order CEC > organic C > pH. In the climate land quality group, month of the dry season with median membership value of 0.64 is the most limiting, whereas relative humidity with median membership value of 0.93 is the least limiting. The limitation of land characteristics for cocoa production in the study area is in the order of CEC > sand > clay > slope > months of dry season > annual rainfall > drainage > relative humidity > organic C > pH.

The relationship between cocoa yield and land suitability index is shown in Fig. 3. The regression equation ($P < 0.001$) indicates that cocoa yield decreases by 16kg ha^{-1} for every 1% decline in soil quality index. The spatial pattern of yield (Fig. 4) reveals that the lowest yields are obtained around close to the center of the study area. The yield map could be used for several purposes including site selection, planning of land improvement and estimation of profitability of cocoa production when combined with other economic data.

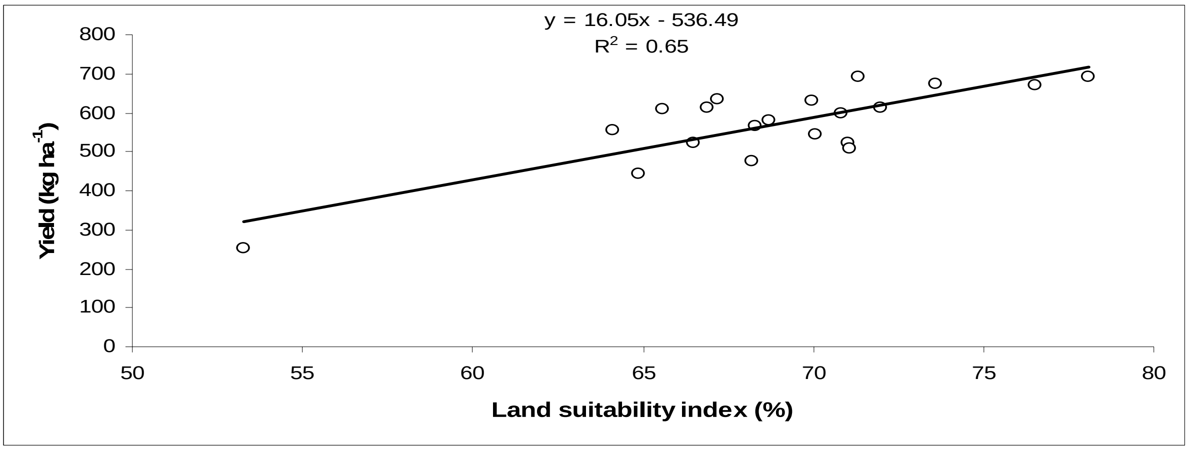

Fig. 2. Relationship between cocoa yield and land suitability index

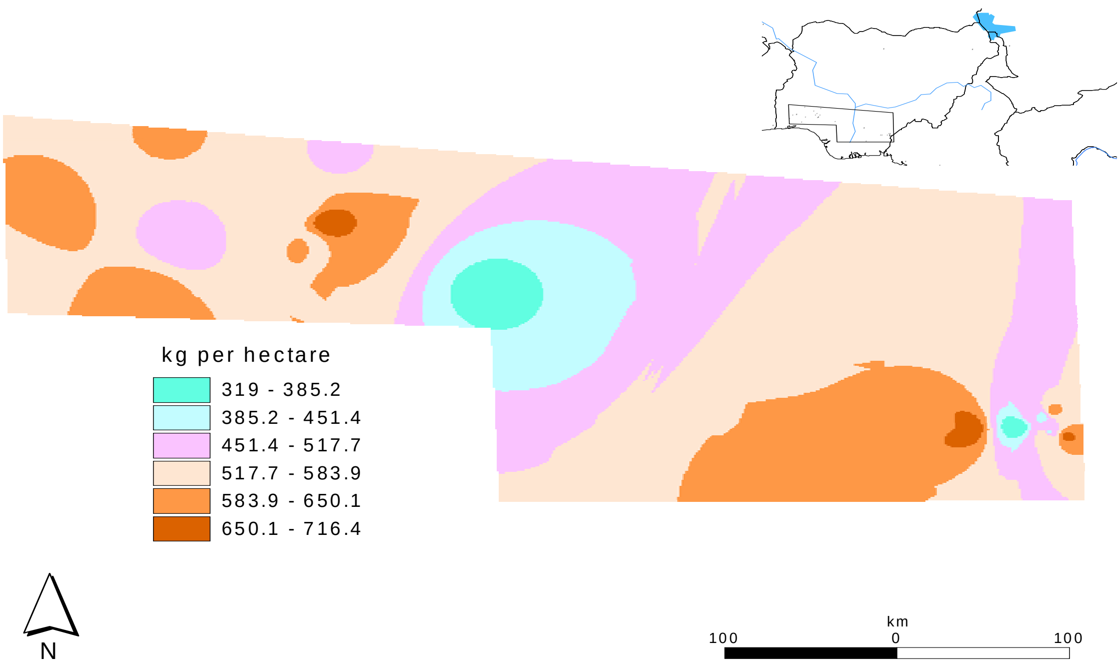

Fig. 3. Predicted cocoa yield based on the model in Figure 2

The low ECEC observed in the soils is mainly due to the predominantly 1:1 kaolinitic clay of the soils. In particular, the K mole fraction (that is, proportion of exchangeable K in CEC) was very low ranging from 0.25% to 2.94% compared to other cations (Table 1), implying that K is a major constraint in these soils. Large amount of K is lost through leaching when the texture is sandy and the nutrient holding capacity is low (Ogunkunle 1993; Hartemink 2003). Hartemink (2005) noted that nutrient loss due to rain wash was less than 8 $kgha^{-1} yr^{-1}$ for N and P but varies from 38 to more than 100$kgha^{-1}yr^{-1}$ for K under cocoa ecosystems.

This study shows that months of dry season is more limiting than annual rainfall or relative humidity. Indeed, the pattern of rainfall distribution is more important than the annual amount, and cocoa tends to grow better in areas where the annual rainfall is more uniformly distributed throughout the year. For instance, higher cocoa yields are obtained in parts of West Africa where the annual total rainfall of 1300–1500mm is uniformly distributed than in Kerala on the West Coast of India where rainfall exceeds 3000mm and cocoa must be irrigated during the 5-month dry season (Wood and Lass 1985). Opeke (1985) also stated that rainfall effect on cocoa yield is actually dependent on the spread or length of the dry season and water retention capacity of the soil. Alvim (1993) confirmed that rainfall effect on the yield could only be significant if there is the absence of rain for over a period of five months continuously in the year. (Sena-Gomes and Kozlowski, 1987) also gave similar reports on the effect of climate on cocoa production.

The agronomic implication of this study is in threefold. First, ECEC limitation of the soils is often compounded by nutrient 'mining' through pod harvest without fertilizer application. More than 70% of the farmers in the study area do not use fertilizer on cocoa (Ogunlade *et al*. 2009). Therefore, the nutrient holding capacity of the soils needs to be enhanced by incorporation of organic materials into the soil. Fertilizer application will also be required to replace the nutrients being removed through pod harvest thereby reducing the limiting impact of ECEC on cocoa. Secondly, the limiting influence of sand content on cocoa production in the affected area implied highly porous and poorly structured soil prone to leaching. Organic amendment such as cocoa pod husk based compost will be required to enhance water and nutrient retention abilities of these soils. Mulching materials may also be required where there is not enough leaf litter mat on the floor of cocoa plantation to reduce leaching in the wet season and water loss via evaporation in the dry season. Lastly, the limitation imposed on cocoa production by months of dry season in the study area implies that water supplementation (irrigation) will be required especially in locations where there is more than 5 months of dry season (Alvim 1993).

CONCLUSION

The use of fuzzy techniques in this study generated land suitability for cocoa production in the study areas. We also generated a yield map that can be used for land use planning and other decisions. Major constraints to cocoa production in the study area are ECEC, sand content and length of dry season. Increasing soil quality by 1% will lead to an increase in yield of 16kg ha^{-1} in the cocoa growing regions of Nigeria. Soil management practices that will raise the cation exchange capacity of the soil and also conserve soil moisture especially during the dry season need to be adopted to enhance cocoa yield in the study area. In addition, the level of soil organic C should not only be maintained but increased through organic amendment for enhanced ECEC and water holding capacity of the soil.

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