Multi-criteria Land Evaluation for Rice Production using GIS and Analytic Hierarchy Process in Kilombero Valley, Tanzania

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Abstract

A GIS-based multi-criteria land evaluation (MCE) was performed in Kilombero Valley, Tanzania to avail decision makers and farmers with evidence based decision support tool for improved and sustainable rice production. Kilombero valley has been identified by the government and investors for rice production intensification. Five most important criteria for rice production in the area were identified through literature search and discussion with local agronomists and lead farmers. The identified criteria were 1) soil properties, 2) surface water resources, 3) accessibility, 4) distance to markets, and 5) topography. Surveys, on-screen digitizations, reclassifications and overlays in GIS software were used to create spatial layers of the identified criteria. Analytic hierarchy process (AHP) method was used to score the criteria using local extension staff and lead farmers as domain experts on a scale of 0.0 – 1.0. Surface water resource scored the highest weight (0.462) followed by soil chemical properties (0.234). Other criteria and their weight in paranthesis are soil physical properties (0.19), topography (0.052), accessibility (0.036), and distance to market (0.025). The MCE results showed that about 8% of the study area was classified as having low suitability for rice production while only 2% was highly suitable. The majority of the area (about 89%) was classified as having medium suitability for rice production. Since the suitability decision was dominated by the surface water resource criterion, the rice suitability in the study area can be greatly improved by improving the water resources management.

Keywords: AHP, Kilombero Valley, multicriteria land evaluation, lowland rice, suitability analysis.

Introduction

The importance of land cannot be overemphasized. Apart from supporting production of biomass that provides food, fodder, fibre, fuel, and timber; it also provides biological habitats and gene reserves for living organisms, regulates storage and flow of water, as well as acting as source and sink of greenhouse gases, thus regulating climate (FAO, 2015; De Maria, 2019). The availability and suitability of land for different functions vary over the landscape, necessitating its inventory and evaluation for optimal land use allocations and management options (Beek *et al.,* 1997). Land evaluation is concerned with the assessment of land performance for specific land utilization purposes and provides a rational basis for taking land use decisions (FAO, 1985; Dempsey *et al.,* 2017). In agriculture, land evaluation is a prerequisite to achieving optimum utilization of the available land resources for sustainable agricultural production (Perveen *et al.,* 2008; Pan and Pan, 2012).

Many land evaluation frameworks have been developed worldwide. Realizing the importance of land evaluation and land suitability in agriculture, the United Nations Food and Agricultural Organization developed a framework for land suitability (FAO, 1976). This provided basis for some other frameworks and incentives for new frameworks. In Sumatra, the land evaluation computer system (LECS) which based on the FAO framework for predicting local crop yields was developed (Wood and Dent, 1983). Rossiter and Wambeke (1997) developed the automated land evaluation system (ALES) which allows land evaluators to build expert systems. In 2002, Kalogirou developed land evaluation using an Intelligent Geographical Information System (LEIGIS). The above mentioned frameworks and others not listed here have their strengths and limitations, mainly on flexibility, complexity, reliability, geographical area and crop specificities, data inputs, and incorporation in GIS (Nwer, 2006). Among frequently used frameworks for land evaluation is the Multi-Criteria Evaluation (MCE) framework (Chen *et al.,* 2008; Maddahi *et al.,* 2014). Several procedures can be used to achieve MCE. One of the most commonly used is weighted linear combination (Zopounidis and Doumpos, 2002). In this procedure continuous criteria are standardized to a common numeric range and then combined by means of a weighted average. Analytical Hierarchy Process (AHP) is among the most popular Weighted Linear Combination Method used for MCE (Ananda and Herath, 2003; Marinoni and Hoppe, 2006; Cherif Ahmed *et al.,* 2007; Rahman and Saha, 2008; Perveen *et al.,* 2008; Kihoro *et al.,* 2013). AHP is superior to many other weighting methods because it can deal with inconsistent judgments by providing a measure of inconsistency called consistency ratio (Saaty, 1980). The method can also be integrated into other software to provide greater flexibility and accuracy such as in GIS (Marinoni and Hoppe, 2006; Cherif Ahmed *et al.,* 2007; Kihoro *et al.,* 2013).

The objective of this study was to apply a weighted multi-criteria land evaluation procedure to undertake suitability analysis of a part of Kilombero Valley, Tanzania for rice production. Rice is the second most important cereal crop in Tanzania after maize, with over 70% of the production being done by small scale farmers (Bucheyeki *et al., 2011*). The average rice yield per unit area under small scale farms of 1.0 to 1.5 t ha^{-1} is very low and is not keeping pace with the steeply rising demand from local population and neighbouring countries. The Kilombero Valley which covers an area of about 11,600 km^2 presents great potential for expansion and intensification of rice production. However, the achievements and their sustainability depend on making informed decisions which stem from the evaluation of land resources in the context of their suitability as well as sustainability for the rice crop.

Materials and Methods

The Study Area

The study was conducted in Kilombero Valley, Tanzania. The valley is located about 300 km west of the Tanzanian Indian Ocean coast covering about 11000 km^2. The study site covered about 300 km^2 within the valley.

Methods

Identifying Land Evaluation Attributes

Land evaluation attributes for crop suitability analysis are the parameters of which quality and/or quantity affect production of the crop. Literature review and focused group discussions with crop experts, local agronomists and farmers were used in this study to prepare the list of parameters which were analyzed for rice growth suitability. Land attributes identified were topography, surface water resource, accessibility, distance to markets, and soil properties.

Reclassification of the attributes values to a common scale

Since the identified attributes (land evaluation criteria) are measured in different ranges of values, it was necessary to set a conversion reference which would put them into one common scale by doing reclassification. This was done by deriving class values of the attributes based on the meaning of assigned class values of soil pH (Table 1). Values of a parameter indicating suitable conditions for rice production were assigned higher class values, and vice versa, consistent with the pH scale.

Generation of Land Attributes Spatial Information

Procedures for generating spatial information for each criterion are described under their subheadings below.

Surface Water Resources

In the Kilombero Valley, rice is grown on flooded fields. Flooding in this valley is a function of rainfall within the valley, and to a large extent,

Table 1: Assigned values for soil pH classes (modified from Soil Survey Staff (1993)).

Denomination	pH range	Meaning	Assigned class value
Ultra acid	< 3.5	extremely low	0
Extreme acid	3.5–4.4	very low	1
Very strong acid	4.5–5.0	low	2
Strong acid	5.1–5.5	low - medium	3
Moderate acid	5.6–6.0	medium	4
Slight acid	6.1–6.5	high	5
Neutral	6.6–7.3	very high	6

the inflows of rivers from the Udzungwa and Mahenge highlands. Given the small size of the study area, the influence of rainfall was assumed to be uniform throughout the area. Instead, the rivers networks were used to map the surface water resource.

Major rivers were digitized on screen as polylines in ArcMap 10.1 (ESRI, 2010) from 1:50,000 scale Topographic maps sheets 234/1, 234/2, and 234/3 (Survey and Mapping Division, 1983) and 5 m resolution RapidEye satellite imagery. Buffer tool in ArcMap was used to divide distances from the rivers. Buffers were created at 500 m, 1000 m, 1500 m, 2000 m, 2500 m, 3000 m, and lastly 4000 m. The shortest distance was assigned the highest class value (6) while the furthest distance was assigned the lowest class value (0). Classes near the rivers were given higher values, consistent with the knowledge that areas near the rivers and channels have more chances of being flooded and experiencing longer flooding durations than the distant ones.

Accessibility

Accessibility to the rice fields in Kilombero valley is via footpaths and seasonal untarmacked roads. The roads were digitized as polylines from 1:50,000 scale Topographic maps sheets 234/1, 234/2, and 234/3 (Survey and Mapping Division, 1983) and 5 m resolution RapidEye satellite imagery. Buffers were created on the roads to produce 6 linear distance intervals at 1000 m, 2000 m, 3000 m, 4000 m, 5000 m, and 6000 m. The shortest distance to the road was given a value of 6 while the furthest distance was given class value of 1.

Distance to Markets

During harvesting period, buyers set buying posts and send agents to the village centers. These village centers therefore acts as market centers. Village centers coordinates were recorded during the field work and were mapped as points to produce market centers' map. Buffers were created around the market centers to create distance spatial data. The distances were divided into 7 classes. The class distances were 1 km, 2 km, 3 km, 4 km, 5 km, 6 km, and 7 km. The 1 km distance was given the highest class value (6), while the last distance class was given the lowest class value (0).

Topography

1 arc (approximately 30 m resolution) Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) (USGS, 2000) was used to derive the slope of the study area. The DEM was preprocessed by filling sinks using algorithm developed by Planchon and Darboux (2001). The slope of each cell was determined by the rate of elevation change in the direction of steepest descent using algorithm in Whitebox Geospatial Analysis Tool following the formula by Horn (1981). Slope gradient raster map in degrees was reclassified to 6 classes: 0-1, 1-2, 2 – 5, 5 – 8, 8 – 15, and >15. The lowest slope gradient class was given class value of 6, while the steepest class was given class value of 1. Lower slope gradients are given higher class values because surface runoff decreases with slope gradient.

Soil Properties

Soil properties were retrieved from a digitally predicted soil cluster map (Massawe *et al.,* 2018). Topsoil attribute values of the soil clusters generated during numerical clustering process (Massawe, 2015) were used. Two reclass maps were developed from soil data: one for soil physical properties and the other for soil chemical properties.

To get soil physical properties reclass map, topsoil sand content of the soil clusters was reclassified. Initially, soil depth was also included in soil physical properties analysis, but later dropped because all soil observations showed there was no soil depth limitation. Higher sand contents in soil leads to increased infiltration rates. The sand classes were 48 – 55%, 55 – 65%, 65 – 75%, 75 – 85%, and > 85%. The class with lowest sand content was given a high class value of 5, while the highest sand content was given class value of 1 as high sand content leads to water loss through infiltration as opposed to soils with less sand content.

The soil chemical properties reclass map was developed after overlay of reclassified pH, CEC, OC, TN, available P, exchangeable K, and Zn maps. Soil pH, CEC and organic carbon were selected because they are among stable indicators of soil quality. N, P and K were selected because these have been identified as the major limiting plant nutrients in Kilombero Valley (Massawe and Amuri, 2012). Zn was selected from the list of studied micronutrients because Cu, Fe, and Mn levels were generally above the limiting values and below the toxic levels. Guides to ratings were Msanya et al. (2001) for CEC, OC, TN, P, and K; De Data (1989) for Zn; Soil Survey Staff (1993) for soil pH; and Hazelton and Murphy (2007) for CEC.

Criteria Weighing

The criteria weights were assigned using AHP method developed by Saaty (1980). Local extension staff and lead farmers were used to assign weights to the identified criteria. The weights of the criteria used in this study as derived by local extension staff and lead farmers are summarized in Table 2.

Table 2: Weights and ranks assigned by a group of lead farmers and extension staff to the criteria identified for rice suitability analysis

Criteria	Assigned AHP derived weight	Rank
Soil physical properties	0.19	3
Soil chemical fertility	0.234	2
Accessibility	0.036	5
Distance to market	0.025	6
Surface water resources	0.462	1
Topography	0.052	4

Predicting Rice Suitability Map

Weighted overlay (MCE) tool in Whitebox GAT was used to produce the rice suitability map. Weights assigned to each criterion through AHP (Table 2) were employed to dictate contribution of each criterion layer in the overlay process. The final map class values ranged from 1.2703 to 5.3163. The map was then reclassified into classes values and meaning falling into that range based on the soil pH common scale (Table 1); 1 – 2 = 1 (very low suitability), 2 – 3 = 2 (low suitability), 3 – 4 = 3 (low to medium suitability), 4 – 5 = 4 (medium suitability), and 5 – 6 = 5 (high suitability). Area for each suitability class was calculated using Area tool in the Whitebox GAT.

Results and Discussion

Accessibility Suitability

The rice suitability of the study area based on accessibility is shown on Fig. 1. Most of the area (59 %) was classified as very highly suitable (Table 3), meaning most fields are connected by roads and paths and are accessible when the area is not flooded. However, during flooding most of the areas are mainly accessed only on foot, power tillers and by bicycles. Apart from

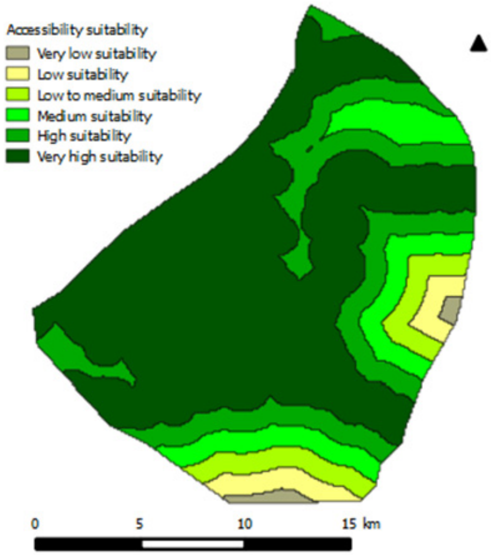

Figure 1: Rice production suitability based on accessibility

this perception might change when more mechanization in other agronomic practices such as weed control will be employed.

Market Accessibility Suitability

About 40% of the study area is located where it can be categorized as having high market suitability for rice production. About 25% are medium suitable, while about 35% are generally marginally suitable by being far from market centers (Table 4). The distribution of the market access suitability area is shown on Fig. 2. Despite the importance of distance to market centers, the dynamics of the markets in the study area are greatly influenced by the yield and amount of rice in the market. When yields are generally good, the competition among the buyers is low and farm gate prices are low. Some farmers would opt to store and wait, anticipating for a better price with time. Some farmers are compelled to sell, nevertheless, in order to meet financial needs such as paying for harvesting and transportation costs.

Table 3: Percentage of areas suitable for rice production based on accessibility

Class Value	Meaning	Area (m^2)	% of total area
1	very low suitability	2,891,700	1.0
2	low suitability	11,072,700	3.7
3	low - medium suitability	17,196,300	5.7
4	medium suitability	32,205,600	10.8
5	high suitability	58,077,000	19.4
6	very high suitability	178,062,300	59.5

flooding, the other accessibility limitation is lack of bridges to facilitate river crossing. The accessibility map was developed based on the distance to the roads, but did not consider the roads conditions and if they are passable all year round.

The accessibility was not perceived as a very important attribute for rice production where it was given a weight of 0.036 in a 0 – 1 scale (Table 2). This could be because the farmers and local extension staff see that most activities heavily requiring mechanization are done before and after flooding. Currently mostly mechanized rice production activities in the study area are land preparation where tractors are increasingly used and transportation of harvested rice where trucks and other vehicles are used. However,

Topographic Suitability

Topographic suitability was derived from slope gradient. Other topographic derivatives such as slope aspect and elevation were not used because of the relative flatness of the study area. The dominant slope gradient range is 2 – 5 degree. This occupies 59% of the study area and is classified as medium suitable for rice production. About 35% of the area has slope gradient below 2 degrees and is classified as highly suitable for rice production (Table 5).

The topographic suitability is classified based

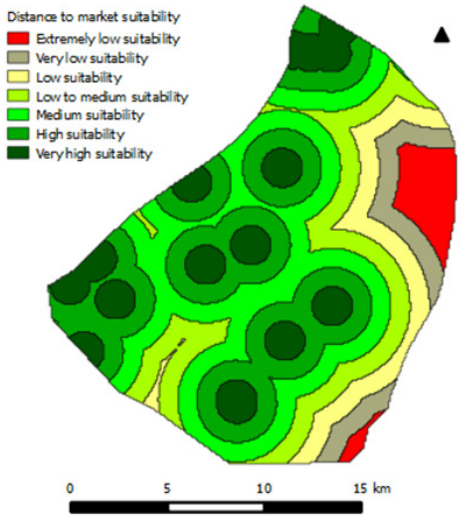

Figure 2: Rice production suitability based on distance to market

physical properties suitability map for this study (section 3.5). In the study area, the relatively high slope areas are used for settlement and growth of upland crops such as maize, beans, cocoa, banana, and a variety of trees for fruits and timber. These areas are also used for grazing, especially when rice fields are flooded and the crop is in the field.

Surface Water Resources Suitability

The surface water resource suitability is displayed on Fig. 3. About 15% of the study area is classified as being of low suitability to rice production based on their distance from the surface water resources (Table 6). These areas are likely to have less chances of being flooded, also are likely to have short durations of flooding because of the small amount of flood water they are likely to get due to being far from the water resources.

Table 4: Percentage of area suitable for rice production based on distance to market

Class Value	Meaning	Area (m^2)	% of total area
0	extremely low suitability	15,568,200	5.2
1	very low suitability	17,795,700	5.9
2	low suitability	26,470,800	8.8
3	low - medium suitability	44,396,100	14.8
4	medium suitability	74,876,400	25.0
5	high suitability	79,979,400	26.7
6	very high suitability	40,419,000	13.5

on influence of slope gradient to surface runoff and water loss. Steeper slopes are known to favour faster surface runoff restricting water ponding as opposed to gentle slopes. However, this should be interpreted in conjunction with the ability of the soil to retain surface water. Due to this, soil texture has been used to develop soil

Other factors such as infiltration which is dictated by soil physical properties and slope gradients are also important in deciding the duration and amount of flooding. So, interpretation of flood related suitability of rice production need to consider in unison, surface water resources, topography, and soil physical properties. All

Table 5: Percent of areas suitable for rice production based on topography

Class Value	Meaning	Area (m^2)	% of total area
1	very low suitability	226,800	0.1
2	low suitability	4,341,600	1.4
3	low - medium suitability	11,939,400	4.0
4	medium suitability	177,916,500	59.4
5	high suitability	96,705,900	32.3
6	very high suitability	8,367,300	2.8

these attributes were finally considered at the end for the analysis of the suitability of rice production using multi-criteria analysis.

Table 6: Percentage of areas suitable for rice production based on their distance to surface water resources

Class Value	Meaning	Area (m^2)	% of total area
0	extremely low suitability	2,932,200	1.0
1	very low suitability	6,836,400	2.3
2	low suitability	13,721,400	4.6
3	low - medium suitability	22,923,000	7.7
4	medium suitability	92,680,200	30.9
5	high suitability	70,923,600	23.7
6	very high suitability	89,488,800	29.9

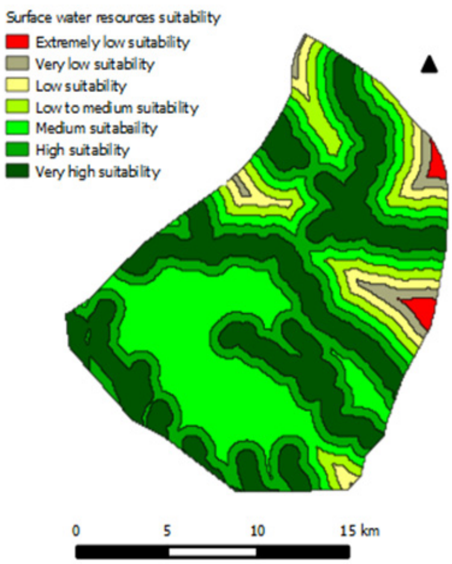

Figure 3: Rice production suitability based on distance to surface water resources

Soil Physical Properties Suitability

As described in the methodology section, this layer was developed using sand content because other soil physical properties such as soil effective depth were not variable to influence suitability rankings. Other soil physical properties such as bulk density and infiltration rates were not determined and are generally related to soil texture (Lal and Shukla, 2005).

Most of the study area (56%) was estimated to have sand contents which are low to medium suitable for low land rice production (Table 7). Only about 10% of the area is having finer textures which would hold water relatively well for paddy rice which prefers ponding conditions. Obviously, this criterion looked soil texture on the side of water ponding, and neglected other factors such as workability and rooting. However, it has been previously documented that farmers would prefer flooded fields because the condition also helps to manage weeds (Massawe and Amuri, 2012).

Table 7: Percentage of areas suitable for rice production based on soil physical properties

Class Value	Meaning	Area (m^2)	% of total area
1	very low suitability	46,364,400	15.5
2	low suitability	53,549,100	17.9
3	low - medium suitability	168,949,800	56.4
4	medium suitability	8,375,400	2.8
5	high suitability	22,266,900	7.4

Soil Chemical Fertility Suitability

The soil chemical suitability was found to range from low to medium. About 63% of the area is classified as of medium soil fertility suitability, while the rest have lower suitability (Table 8). The areas which showed low suitability are generally those closer to the escarpment. Historically, the areas closer to the escarpment were put into agriculture earlier than those close to the main Kilombero River at the center of the valley (Kato, 2007). Fertility management in the study area by application of fertilizers and conservation agriculture is very low (Massawe and Amuri, 2012). Use of fertilizers is low because of lack of awareness and affordability by small scale farmers. Another factor is the fluctuation of the rice prices, such that farmers are not sure of getting returns if the farm gate prices are low. There is general inadequacy of knowledge about use of conservation agriculture. Disc plowing is very popular currently, residues are burned or grazed on, and a few farmers apply blanket recommended N, P, K, and S containing fertilizers (Massawe and Amuri, 2012).

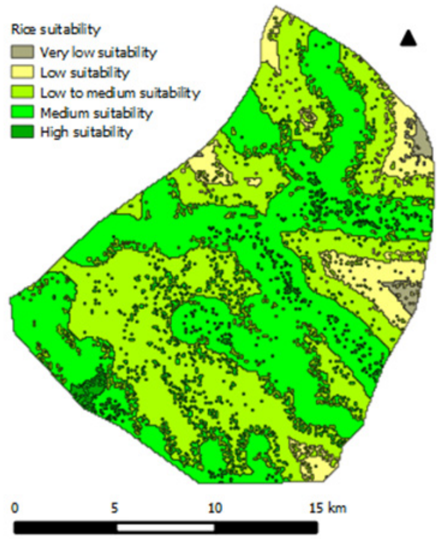

Figure 4: Rice production suitability based on the six identified suitability analysis criteria

suitability for rice production while only 2% is highly suitable. The majority of the area (about 89%) is classified as having medium suitability for rice production (Table 9).

Table 8: Percentage of areas suitable for rice production based on soil chemical fertility

Class Value	Meaning	Area (m^2)	% of total area
2	low suitability	5,443,200	1.8
3	low - medium suitability	103,939,200	34.7
4	medium suitability	190,123,200	63.5

Overall Rice Suitability

The overall suitability of the study area for rice production based on the 6 identified criteria (accessibility, markets, topography, water resources, soil physical properties and soil chemical properties) is displayed on Fig. 4. About 8% of the area is classified as having low

Being a lowland rice production area, the dominance of surface water resources for the suitability of an area is clearly seen. Areas closer to the water sources have generally higher suitability values, a result of higher weights given to the criterion by the farmers

Table 9: Percent of areas suitable for rice production based on the six identified rice suitability analysis criteria

Class Value	Meaning	Area (m^2)	% of total area
1	very low suitability	3,102,300	1.0
2	low suitability	22,396,500	7.5
3	low - medium suitability	127,113,300	42.4
4	medium suitability	141,669,000	47.3
5	high suitability	5,216,400	1.7

and extension staff (Table 2). The dominance of the water resource implies that the suitability can be greatly improved by managing the water resources. This may include constructions of soil bunds to restrict surface lateral movement of water once they have entered the fields. Construction of irrigation schemes will also be very useful. However, the major challenge here is the soil textures which are generally coarse resulting to higher infiltration rates (Bonarius, 1975; Massawe, 2015).

Improved fertility management can also have big influence in rice production suitability of the study area. Soil testing and site specific application of fertilizers will be very beneficial. As such, except for soil pH, CEC, and OC, the rest of the soil chemical fertility limitations can be addressed and improved by timely and appropriate application of organic and mineral fertilizers.

Access to rice fields and markets can be greatly improved by improving roads and bridges infrastructures. This can be local or central government efforts which would greatly improve mobility and reduce transportation costs, thus improving marketing and productivity of rice.

Conclusion

This study has developed a land suitability map for rice production for a portion of Kilombero Valley using multi-criteria analysis, AHP and GIS. About 8% of the area is classified as having low suitability for rice production while only 2% is highly suitable. The majority of the area (about 89%) is classified as having medium suitability for rice production.

The suitability decision was dominated by the surface water resource criterion and soil fertility attributes, out of 6 attributes identified and used in the analysis. The suitability of the study can therefore be improved by addressing issues related to surface water and soil fertility.

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