Mapping land suitability for maize (*Zea mays* L.) production using GIS and AHP technique in Zimbabwe

Walter Chivasa[a,b], Onisimo Mutanga[b] and Chandrashekhar Biradar[c]

[a]Seed Co Ltd, Rattray Arnold Research Station, PO Box CH 142, Chisipite, Harare, Zimbabwe, walter.chivasa@seedcogroup.com;
[b]School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, P/Bag X01, Scottsville, Pietermaritzburg 3209, South Africa;
[c]Geoinformatics Unit, International Centre for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt.

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Abstract

The study integrates geographic information system (GIS) and analytic hierarchy process (AHP) to evaluate land suitability for maize production in Zimbabwe using multi-criteria evaluation (MCE) process. Four thematic maps based on rainfall, temperate, soil type and slope were integrated through overlay technique in a GIS environment to produce maize production suitability map. The resultant maize suitability map was overlaid with constraints map to 'mask out' all non-agricultural land. The final maize suitability map shows that 3.20% of the total land is highly suitable, 16.56% is suitable, 25.34% is moderately suitable, 32.33% is marginally suitable and 9.57% is not suitable for maize production in its current form. The maize suitability classification was validated by regression analyses using measured maize grain yield of 5 key maize varieties representing 5 different maturity groups. Grain yield was regressed against suitability index (SI) of each land class. There were significant positive correlations between maize grain yield and land suitability classes (R^2 = 0.63 - 0.85). Integrating GIS and AHP with MCE is effective in assessing land suitability for targeting location specific interventions for maize production and the result is a comprehensive suitability map for Zimbabwe, incorporating several critical environmental factors affecting maize adaptation. We recommend the use of this suitability map as a decision support tool in land use planning and policy making.

***Keywords**: Mapping maize land suitability, Geographical Information System, Multi-criteria evaluation, Analytic hierarchic process, Zimbabwe*

1. Introduction

Land suitability evaluation involves the determination of the level of fitness of a given piece of land for a certain type of use (Akinci *et al*. 2013). It refers to how close the properties of the land unit satisfy the requirements for a specified purpose when all the relevant critical factors are considered (FAO 1976; Beek *et al.* 1987; Steiner et al. 2000; Al-Shalabi *et al*. 2006). Zimbabwe is classified into five agro-ecological zones based on a single factor (rainfall) analysis (Vincent and Thomas 1960), yet crop production is affected by a complex interaction of many factors. The zonation by Vincent and Thomas (1960) produced a rainfall suitability map. Complete land suitability analysis takes into account all relevant physical environmental, climatic and socio-economic factors. However, socio-economic conditions can readily be manipulated and modified by human interventions and therefore are more time-dependent. The physical environmental and climatic factors are known to be more stable over time (Dent and Young 1981; Van Lanen 1991; Triantafilis *et al*. 2001; Zhang *et al*. 2015). Accordingly, land suitability analysis for producing maize is largely based on environmental and climatic factors (Van Ranst *et al*. 1996).

Comprehensive land suitability evaluation integrates three factors of an environment (location, environmental constraints and uses) and provides a more integrated view of their interactions (Al-Shalabi *et al*. 2006; Keshavarzi *et al*. 2010). This more inclusive but also compound approach presents some challenges since the level of significance of factors affecting land suitability are not equal (Elsheikh *et al*. 2013). The need to consider different factors of varying importance simultaneously makes land suitability assessment a more complex exercise (Duc 2006; Bandyopadhyay *et al*. 2009; Akıncı *et al*. 2013). In practice, the relative importance of factors affecting land suitability are determined based on expert knowledge (Saaty 1977; Eastman 2012). GIS-based land suitability evaluation has been proven to be a powerful tool in integrating physical environmental factors of varying level of importance with expert knowledge into land suitability mapping (Carver 1991; Malczewski 2004). The process of combining physical environmental factors and expert knowledge to produce crop suitability maps with high explanatory power, and how assessments are compared and used, is known as the decision rule, which can either be simple or complex depending on the number of factors involved and included in the model (Eastman *et al*. 1995). Because several factors and various criteria are involved, land suitability analysis is best described as a multi-criteria evaluation (MCE) problem (Reshmidevi *et al*. 2009).

The most commonly used procedures in MCE are weighted linear combination (WLC) (Eastman *et al*. 1995), concordance-discordance analysis (Voogd, 1983; Carver, 1991) and Boolean overlay technique (Malczewski 2004). Concordance-discordance analysis is computationally complex when many factors are involved. The Boolean procedure has some challenges of classifying land units based on a precise, often binary definition (suitable or not suitable) (Banai 1993). The Boolean logic does not allow part-membership. Membership is limited to two definitions, 0 (if element is not in set) and 1 (if element is in the set). WLC is now the most widely used procedure in MCE, where factors are assigned weights and combined through summation to yield a balanced suitability map in a GIS environment.

Determination of the relative weights of factors is done through pairwise comparison procedure known as the analytic hierarchy process (AHP) developed by Saaty (1977) and applied in several studies (Akinci *et al*. 2013; Zhang *et al*. 2015; Mu and Pereyra-Rojas 2017). AHP has been found to be the most suitable process for handling multi-criteria data, which are heterogeneous in nature. The AHP process requires expert knowledge to derive priority measurements of complete judgements that show exactly by how much one factor dominates the other with respect to a given attribute (Saaty

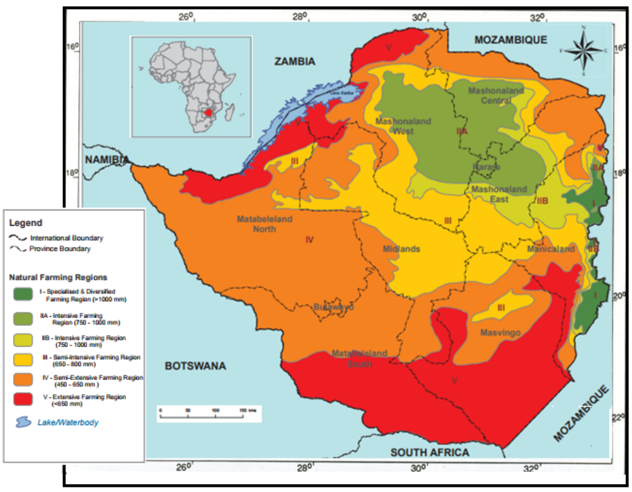
1977; Saaty 2008). However, the judgements might be inconsistent and measuring inconsistency to improve the judgements is the strength of the AHP approach. AHP enables the understanding of complex problems through decomposing them into hierarchical structures depicting the connection of the goal, criteria and sub-criteria. The criteria and sub-criteria are pairwise compared to obtain a measure of relative importance and comparative scales. Pairwise comparison creates a ratio matrix to simplify an otherwise complex process and calculates reliability or discrepancy of the comparisons through a consistency ratio (CR) (Saaty 2002). Once the factors are rated and weighted using AHP, they are analysed in a GIS environment using the overlay technique (Malczewski 2004).

This study integrates GIS and AHP in a MCE process to map land suitability for maize production in Zimbabwe using 24 factors. Maize is the most preferred staple food crop in Zimbabwe cultivated by more than 80% of the farmers and provides more than 50% of the calorie requirements (Rukuni *et al*. 2006). Understanding land suitability for maize production is the basis for sustainable land utilization and increased productivity.

2. Materials and Methods

2.1. Study area

The study was conducted in Zimbabwe (Figure 1). Zimbabwe lies between latitudes 15°37′S to 22°24′S and longitudes 25°14′E to 33° 04′E. The country is classified into five agro-ecological zones termed Natural Regions (NR). NR *I* is the wettest (>1050 mm per annum (p.a.)) and covers just 1% of the country. NR *II* receives 750 – 1000mm p.a. and covers 15% of Zimbabwe. NR *III* averages 650 – 800mm p.a., covering 19% of the total area. NR *IV* has an annual rainfall of 450 – 650mm p.a., covering about 38%. NR *V*'s poorly distributed rainfall is usually less than 450mm p.a. and covers about 27% of the country's land area. The steps followed in this study to generate a land suitability map are briefly described below:



Source: Department of the Surveyor-General, Zimbabwe.

Figure 1. The location of study area (Zimbabwe) showing agro-ecological regions (natural farming regions) and Provinces. Insert shows the location of study area in Africa.

2.2. Establishing the criteria: factors and constraints

Criteria were established from the literature and expert knowledge and were identified as environmental (soil type and slope gradient) and climatic (rainfall and temperature). Literature and experts identify rainfall (Huajun and Van Ranst 1992, Elsheikh *et al*. 2013), temperature (Herrero and Johnson 1980; Schoper *et al*. 1987; Dupuis and Dumas 1990; Hatfield and Prueger 2015), soil type (Braimoh et al. 2004; Albaji *et al*. 2009) and slope gradient (Bandyopadhyay *et al*. 2009; Bagherzadeh and Mansouri Daneshvar 2011) as major factors determining maize growth. These factors were used in this study to analyse land suitability for maize production. Non-agricultural land (national parks, forests, water bodies and built-up areas) were identified as constraints. Factors such as aspect, elevation, day length, relief, growing degree days, soil pH were not considered in this study. Rainfall, temperature, soil types and slope gradient suitability ranges used in this study are given in Table 1.

Table 1. Criteria used in suitability mapping and their brief descriptions

Criteria	Sub-criteria	Class	Suitability range	Description	Reference
Rainfall	Rain1	*I*	≥ 901 mm	High rainfall ranging from 900 mm and above. Rainfall in this area is well distributed during maize growth period (Nov - April). Receives above 18 rain pentads per season and is very reliable	Vincent & Thomas 1960
	Rain2	*II*	801 - 900 mm	Recives rainfall in the range of 801 - 900 mm. Receives on average 16-18 rain pentads per season and reliable	Vincent & Thomas 1960
	Rain3	*III*	701 - 800 mm	Rainfall ranges from 701- 800 mm per annum. Receives 14 - 16 rain pentads per season.	Vincent & Thomas 1960
	Rain4	*IV*	601 - 700 mm	Receives moderate in total amount. The area is also subject to mid season dry spells	Vincent & Thomas 1960
	Rain5	*V*	501 - 600 mm	Receives low rainfall, prone to periodic droughts and severe dry spells during the season	Vincent & Thomas 1960
	Rain6	*VI*	400 - 500 mm	Rainfall in this area is too low and erratic for reliable production of even drought-resistant grain crops	Vincent & Thomas 1960
Soil type	Soil1	*I*	Fersiallitic group	Moderate - very deep reddish, brown granular clays formed on mafic rocks.	Thompson 1965; Nyamapfene 1992
	Soil2	*II*	Fersiallitic group	Moderate shallow, geryish brown, relatively silty sandy loams	Thompson 1965; Nyamapfene 1992
	Soil3	*III*	Paraferrallitic group	Sandy soils with substential ferralitic characteristics	Thompson 1965; Nyamapfene 1992
	Soil4	*IV*	Siallitic group	Prodominantly illite or illite-montmorillonoid clay soil, with or without calcareous in the underlying material.	Thompson 1965; Nyamapfene 1992
	Soil5	*V*	Rigosol/Lithosol groups	Sand soils with less than 10% silt + clay above 2 m. Very low silt/clay ratios (so called Kalahari sands).	Thompson 1965; Nyamapfene 1992
	Soil6	*VI*	Sodic group	Soils containing significant amounts of exchangeable sodium within 80 cm of the surface horizons	Thompson 1965; Nyamapfene 1992
Temperature	Temp1	*I*	24 - 28°C	Optimal temperature = highly suitable	Muchow *et al*. 1990; Hatfield and Prueger 2015
	Temp2	*II*	28 - 30°C	Sub-optimal - very suitable	Muchow *et al*. 1990; Hatfield and Prueger 2015
	Temp3	*III*	31 - 32°C	Beyond this growth is affected - still suitable	Muchow *et al*. 1990; Hatfield and Prueger 2015
	Temp4	*IV*	33 - 34°C	Five consecutive days at this results in > 2% yield loss	Muchow *et al*. 1990; Hatfield and Prueger 2015
	Temp5	*V*	35 - 36°C	Leaf firing & pollen death result in large yield losses	Muchow *et al*. 1990; Hatfield and Prueger 2015
	Temp6	*VI*	> 36°C	More than 5 days at this = permanent wilting & death	Muchow *et al*. 1990; Hatfield and Prueger 2015
Slope gradient	Slope1	*I*	0.0 - 5.0 %	Highly suitable	Bandyopadhyay et al. 2009
	Slope2	*II*	5.1 - 10.0 %	Very suitable	Bandyopadhyay et al. 2009
	Slope3	*III*	10.1 - 15.0 %	Suitable	Bandyopadhyay et al. 2009
	Slope4	*IV*	15.1 - 20.0 %	Moderately	Bandyopadhyay et al. 2009
	Slope5	*V*	20.1 - 25.0 %	Marginally suitable	Bandyopadhyay et al. 2009
	Slope6	*VI*	≥ 25.1 %	Not suitable	Bandyopadhyay et al. 2009

I = highly suitable, *II = very suitable*, *III = suitable*, *IV = moderately suitable*, *V = marginal suitable* and *VI = not suitable*.

2.3. AHP approach

The AHP model was made up of goal, criteria and sub-criteria (Figure 2), where the overall objective is the suitability map. In MCE process, the weight of each factor needs to be defined. Relative importance of criteria were assigned using Saaty's scale (Table 2) (Saaty 1977). The pairwise comparison matrix for criteria and sub-criteria were constructed. A scale for evaluation comprising of values from 1 to 9, describing the relative importance of factors over one another was used (Saaty 1977). Twenty-eight scientists (crop breeders, agronomists, soil scientists and climatologists) were requested to give the importance of the factors through consensus following a similar methodology used in other land suitability studies (Eastman 2012; Zhang *et al*. 2015).

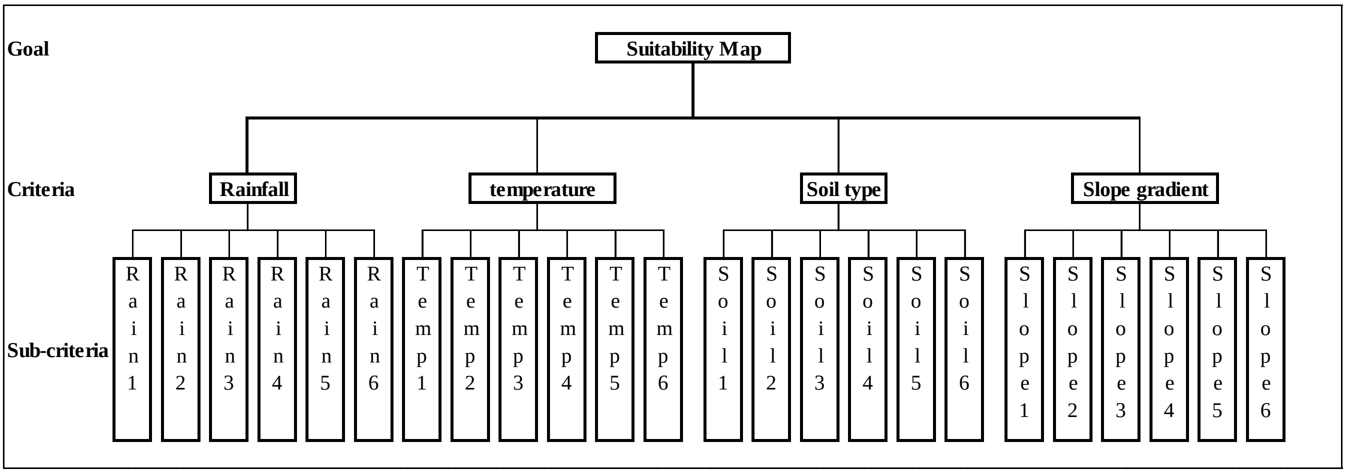


Figure 2. Decision tree model for land suitability analysis using AHP

Table 2. The scale for pair-wise comparison

Intensity of importance	Description
1	Equally important
2	Equally to moderately important
3	Moderately important
4	Moderately to strongly important
5	Strongly important
6	Strongly to very strongly important
7	Very strongly important
8	Very strongly to extremely important
9	Extremely important

Source: Saaty (1977)

A pair-wise comparison matrix for the sub-criteria was constructed and normalized to obtain the suitable weights and the CR (Table 3). The 4 × 4 matrix comprises all the pair-wise comparisons for the four criteria. Weights and eigenvalues were calculated using geometric mean procedure where the n^{th} root of the product of the pair-wise comparison values in each row of the matrices was determined (Saaty 1983). The n^{th} root was normalized by dividing each n^{th} root value by their sum to obtain the corresponding weights. If a matrix is of the order n (total elements in comparison), then the total number of judgements needed is given by $(n^2 - n)/2$ with diagonal elements being equal to unity since it is a reciprocal (Saaty 1987). When comparing a pair of factors (*i*,*j*) in a matrix, with *i* on the left side of the matrix and *j* on top of the matrix, the objective is to see which factor is more important and by how much, using the scale developed by Saaty (1977) (Table 2). This gives a_{ij} (or a_{ji}), while the reciprocal value is entered for the transpose, where a_{ij} is relative importance value of factor *i* relative to factor *j* in the matrix.

Table 3. Pair-wise comparison of relative importance of sub-criteria

	Rainfall	Soil type	Temperature	Slope gradient	Weight
Rainfall	1	5	7	9	0.652
Temperature	0.143	1	5	7	0.231
Soil type	0.125	0.143	1	5	0.085
Slope gradient	0.111	0.125	0.143	1	0.033

Max. Eigenvalue (λ_{max}) = 4.1772; n = 4; Consistency Index (CI) = (λ_{max} – n)/(n-1) = 0.0591; RI = 0.89; Consistency Ratio (CR) = CI/RI = 0.07

Lambda-max (λ_{max}) was determined by adding the columns of the matrix of judgements and multiply the resulting vectors by the priority vector (weight) then sum the products following Saaty's method (Saaty 2002). The sum yielded the eigenvalue denoted by λ_{max}. The consistency index (CI) was determined using Saaty (1977; 2012)'s equation (1):

$$\mathrm{CI} = \frac{(\lambda\mathrm{max} - n)}{n-1} \qquad [1]$$

Where λ_{max} is the largest or principal eigenvalue of the matrix, and *n* is the number of criteria or factors being compared. The CI equation has been applied in similar work by Akinci *et al.* (2013), Zhang *et al.* (2015) and Mu and Pereyra-Rojas (2017). The CR was calculated using Saaty (1996)'s equation (2):

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \qquad [2]$$

Where RI is the Random Index (Table 4), determined by Saaty and Tran (2007). CR is a measure of the decision maker's consistency when rating the factors used in the pair-wise comparisons. It is the measure of departure of λ_{max} from *n*. It shows the likelihood that the ratings were developed by chance. The ideal CR is zero (0). However, in practice achieving zero is difficult. To be accepted the CR must be $\leq$ 10%, and if CR > 10% then the decision maker should re-evaluate the pair-wise comparison to identify the source of inconsistency and resolve it and repeat the analysis until CR reaches an acceptable level (Saaty 1996).

Table 4. The Random Indices

N	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0.00	0.00	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Source: Saaty and Tran (2007)

The second step of AHP involved determination of relative ratings of each sub-criteria. Each matrix of the sub-criteria was of the order of 6 × 6 (Table 5). The λ_{max}, CI (equation 1) and CR (equation 2) were determined. Finally, the land suitability index (SI) was obtained by combining each factor weight (W*i*) with factor score (X*i*) to get a suitability value for each land unit following a similar approach used by Bagheri *et al*. (2013), Malczewski (2004) and Feizizadeh and Blaschke (2013) using equation (3):

$$SI = \left(\sum_{i=1}^{n} Wi \times Xi\right) \times \Pi Ci \qquad [3]$$

Where SI is the suitability value, W*i* is the weight of factor *i*, X*i* is the criterion score of factor *i*, C*i* is the constraints (Boolean value), and Σ is the sum and Π is the product. SI lies between 0 and 1 because values of both W*i* and X*i* are between 0 and 1. In this case values near zero represent unsuitable areas, while those near one indicate highly suitable areas. Since C*i* is the land use constraint, it only takes a value of either 0 or 1 (Boolean logic), where zero was assigned to protected land (national parks and forests) and non-agricultural land (built-up areas and water bodies) and 1 represents current and potential croplands.

Table 5. Pair-wise comparison of relative importance of classes

(a) Rainfall

	Rain1	**Rain2**	**Rain3**	**Rain4**	**Rain5**	**Rain6**	**Weight**
Rain1	1	3	5	7	8	9	0.4559
Rain2	0.333	1	3	5	7	8	0.2632
Rain3	0.200	0.333	1	3	5	7	0.1423
Rain4	0.143	0.200	0.333	1	3	5	0.0744
Rain5	0.125	0.143	0.200	0.333	1	3	0.0410
Rain6	0.111	0.125	0.143	0.200	0.333	1	0.0232

(b) Temperature

	Temp1	**Temp2**	**Temp3**	**Temp4**	**Temp5**	**Temp6**	**Weight**
Temp1	1	2	3	4	5	6	0.4014
Temp2	0.500	1	2	3	4	5	0.2364
Temp3	0.333	0.500	1	2	3	4	0.1689
Temp4	0.250	0.333	0.500	1	2	3	0.0886
Temp5	0.200	0.250	0.333	0.500	1	2	0.0600
Temp6	0.167	0.200	0.250	0.333	0.500	1	0.0448

(c) Soil type

	Soil1	**Soil2**	**Soil3**	**Soil4**	**Soil5**	**Soil6**	**Weight**
Soil1	1	2	3	4	5	7	0.3870
Soil2	0.500	1	2	3	4	5	0.2493
Soil3	0.333	0.500	1	2	3	4	0.1587
Soil4	0.250	0.333	0.500	1	2	3	0.1000
Soil5	0.200	0.250	0.333	0.500	1	2	0.0639
Soil6	0.143	0.200	0.250	0.333	0.500	1	0.0410

(d) Slope gradient

	Slope1	**Slope2**	**Slope3**	**Slope4**	**Slope5**	**Slope6**	**Weight**
Slope1	1	1	3	4	5	6	0.3518
Slope2	1	1	1	3	4	5	0.261
Slope3	0.333	1	1	1	3	4	0.1662
Slope4	0.250	0.333	1	1	1	3	0.1047
Slope5	0.200	0.250	0.333	1	1	1	0.0669
Slope6	0.167	0.200	0.250	0.333	1	1	0.0495

a) Max. Eigenvalue (λ_{max}) = 6.5068; n = 6; Consistency Index (CI) = 0.1014; Consistency Ratio (CR) = 0.08;
b) Max. Eigenvalue (λ_{max}) = 6.1934; n = 6; Consistency Index (CI) = 0.0387; Consistency Ratio (CR) = 0.03;
c) Max. Eigenvalue (λ_{max}) = 6.0217; n = 6; Consistency Index (CI) = 0.0043; Consistency Ratio (CR) = 0.04;
d) Max. Eigenvalue (λ_{max}) = 6.1075; n = 6; Consistency Index (CI) = 0.0215; Consistency Ratio (CR) = 0.02; Random Index (RI) = 1.24.

2.4. Digitizing and overlay of thematic maps

The thematic maps used in this study are shown in Figure 3. The maps (soil type, temperature, rain fall and slope gradient) were obtained from the Surveyor General of Zimbabwe's office. Spatial databases were created by geo-referencing, digitization, vectorization and rasterization of thematic maps using ArcGIS (ArcGIS 10.3) and each reclassified into six different land suitability classes (Figure 3a – 3d). The Digital Elevation Model (DEM) (20m contour interval) was used to generate a slope gradient layer (Figure 3d).

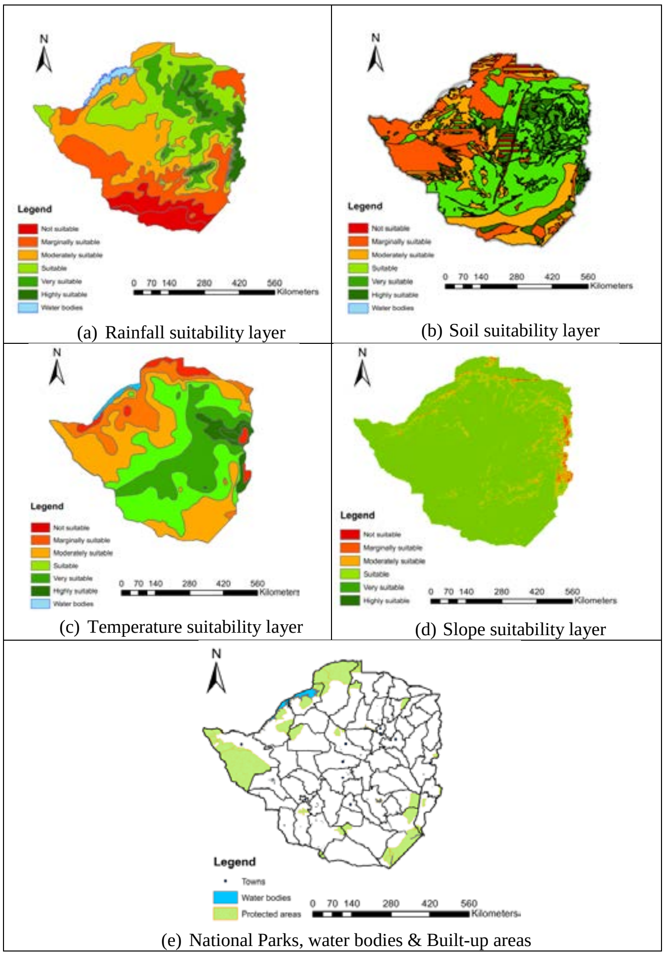


Figure 3. Maps for the significant layers used to generate the maize land suitability map: (a) rainfall, (b) soil type, (c) temperature, (d) slope gradient and (e) Parks, water bodies & built-up areas

The thematic maps were aggregated to produce a maize suitability map using the overlay technique in a GIS environment (Eastman *et al*. 1995; Collins *et al*. 2001). The maize suitability map was integrated with the constraints map to "mask out" all protected areas and non-agricultural land (Figure 3e). The size of each land suitability class was determined including the size of protected areas and non-agricultural land.

2.5. Validation using maize yield responses

Finally, linear regression analyses were carried out to validate the final maize suitability classification. Saaty (1977), Bagheri *et al*. (2013) and Zhang *et al*. (2015) suggested that the actual validation of derived suitability classes rests with statistical measures. Long-term maize yield for key varieties were obtained from Seed Co's multi-environment trials (METs) conducted from 2006/2007 – 2016/2017. Measured long-term yields of five key and popularly grown maize varieties representing five different maturity groups (ultra-early $\leq$100 days, very early = 101 – 120 days, early = 121 – 130 days, medium = 131 – 140 days and late = 141 – 150 days) were regressed against the SI value of each land suitability class to validate the classification. The Kolmogorov-Smirnov test was conducted to test for normal distribution of the land classes (Zhang *et al*. 2015).

3. Results and Discussion

3.1. Thematic suitability

The pairwise comparison matrix produced weights shown in Table 3 for annual rainfall, temperature, soil type and slope gradient. The pairwise comparison of sub-criteria yielded normalized weights shown in Table 5. Criteria modelling produced different thematic maps, one for each criterion reclassified into six land suitability classes (Figure 3a – 3d).

3.2. Overall suitability

Integration of all the thematic layers (Figure 3a – d) and "masking" out the constraints in Figure 3e produced a detailed and complete maize suitability map (Figure 4). The map was classified into five suitability classes: *highly suitable*, *suitable*, *moderately suitable*, *marginally suitable* and *not suitable.* The highly suitable class represents land with negligible limitations that are insignificant to affect maize growth. Thus, maize productivity is expected to decrease continuously from highly suitable to marginally suitable land until it is no longer feasible to grow maize (not suitable area) under purely rain-fed conditions. The unsuitable land is that which cannot support maize growth in its current state.

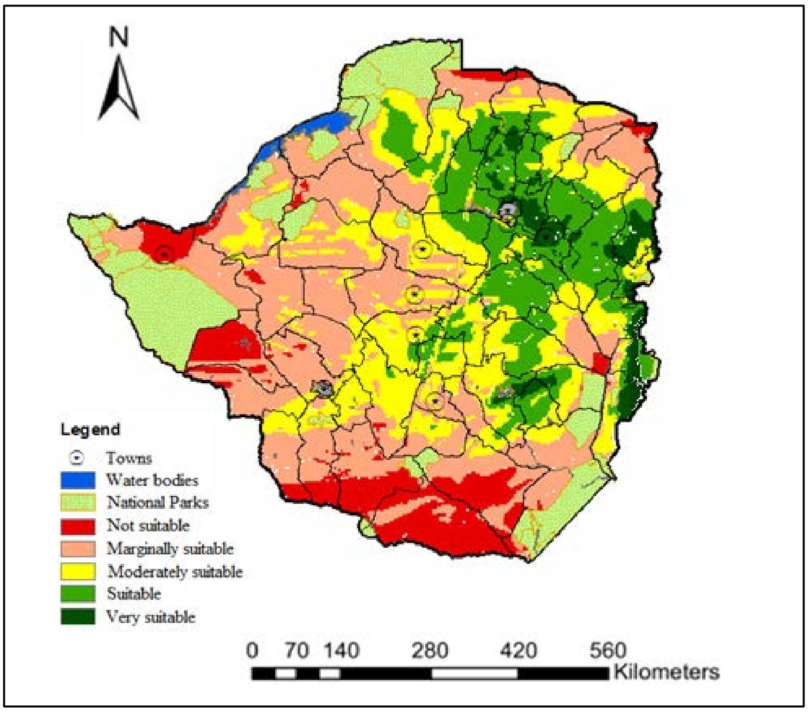


Figure 4. Final land suitability map for maize production in Zimbabwe

The size of the final suitability land classes are given in Table 6. The result shows that only 12,383.50km^2, representing about 3.20% of the total land is highly suitable. Suitable areas occupy 64,065.03km^2, which represents 16.56% of the total area. Together, highly suitable and suitable areas take about 19.76% of the total area and are mainly situated in the north-eastern parts of the country. The mean annual temperatures of these highly suitable and suitable areas range from 24 to 30^{o}C, while their average rainfall per year is between 801 and 900 mm and receives an average of 14 – 16 rain pentads per crop growing season. These are areas characterised by fersiallitic soils with moderate to very deep reddish, brown granular clays soils (Thompson 1965; Nyamapfene 1992) and slopes of 0 – 15%, with excellent drainage.

Land areas classified as moderately suitable are those with slope from 15.1 – 20.0%. The areas cover an area of 98,032.32km^2 and account for 25.34% of the total area. These areas are scattered around the periphery of suitable areas and receive 701 – 800mm annual rainfall, with mean temperatures of 30 – 32^{o}C, and are characterized mainly by loamy and clay loamy soils. Marginally suitable areas constitute 125,051.38km^2, which represent 32.33% of the total area. These are areas, which receive 501 – 600mm rainfall per annum and experience frequent droughts and prolonged dry spells during the crop growing season. The soils of the areas are deep sands with extremely low silt/clay ratios. These are mainly distributed in the south and south-west of the country. Non-suitable areas cover an area of 37,027.27km^2 and represent 9.57% of the total area. The areas are mainly found in the south and west of the country. Most of the soils in these areas are sodic, containing significant amount of exchangeable sodium within 80cm of the surface horizon. Average temperatures are above 35^{o}C and rainfall is below 500mm per annum. The areas experience very erratic rainfall for reliable crop production of even drought resilient varieties.

Table 6. Suitability areas and their distribution for each thematic layer.

Suitability	Area (Km^2)	Area (%)
Rainfall		
Highly suitable	20441.19	5.28%
Very suitable	46856.21	12.11%
Suitable	97794.18	25.28%
Moderately suitable	101098.01	26.13%
Marginally suitable	80081.42	20.70%
Not suitable	40578.99	10.49%
Total	386850.00	100.00%
Temperature		
Highly suitable	19667.45	5.08%
Very suitable	72746.75	18.80%
Suitable	116154.08	30.03%
Moderately suitable	115817.86	29.94%
Marginally suitable	46616.99	12.05%
Not suitable	15846.88	4.10%
Total	386850.00	100.00%
Soil type		
Highly suitable	45362.15	11.73%
Very suitable	147200.06	38.05%
Suitable	15509.40	4.01%
Moderately suitable	73034.95	18.88%
Marginally suitable	94492.48	24.43%
Not suitable	11250.95	2.91%
Total	386850.00	100.00%
Slope gradient		
Highly suitable	246369.08	63.69%
Very suitable	91226.21	23.58%
Suitable	30565.93	7.90%
Moderately suitable	12538.11	3.24%
Marginally suitable	4814.29	1.24%
Not suitable	1336.38	0.35%
Total	386850	100.00%
Overall Suitability		
Very suitable	12383.50	3.20%
Suitable	64065.03	16.56%
Moderately suitable	98032.32	25.34%
Marginally suitable	125051.38	32.33%
Not suitable	37027.27	9.57%
Others (Parks, etc.)	50290.50	13.00%
Total	386850.00	100.00%

Protected land, built-up areas and water bodies defined as constraints in this study constitute about 13.00% of the total land area. The overall suitability distribution is shown in Figure 5. The Kolmogorov-Smirnov test shows that it is not a normal distribution but exhibits a slight left skewness. Land suitability for maize production generally decreases from north-east to south-west of the country. Suitability is high in the north-eastern parts of the country due to high rainfall, deep fertile soils, favourable temperatures and gentle slopes. The bulk of the study area is made up of moderately and marginally suitable areas, together constituting 57.67% of the total potential area available for maize production.

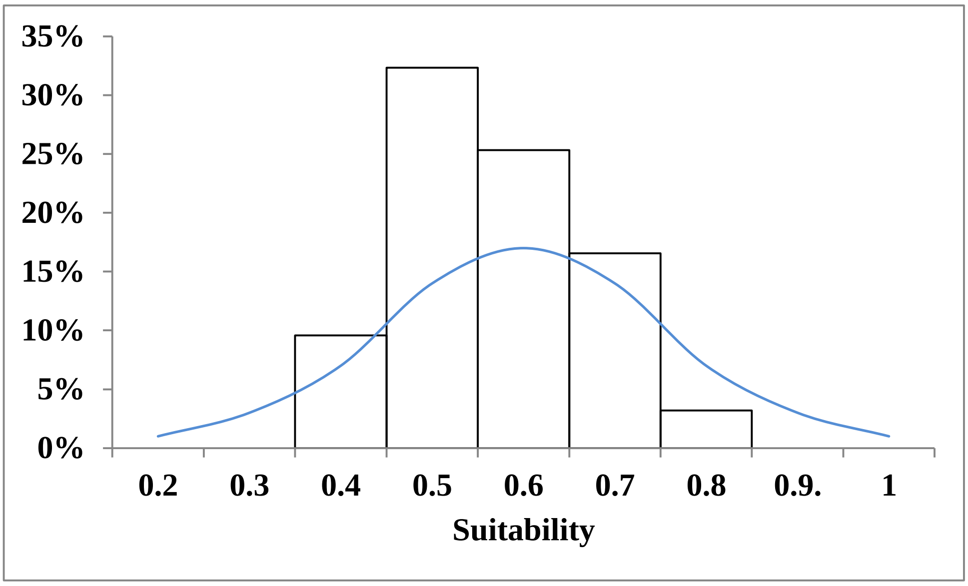


Figure 5. Overall distribution of the land suitability classes (from not suitable to highly suitable). The line graph shows the expected normal distribution.

Using AHP procedure was useful in decomposing an otherwise complex land suitability problem. Arranging factors in a descending hierarchical from the overall goal, criteria and sub-criteria in successive levels reduced a multidimensional problem into a unidimensional one. Once the decision structure was decomposed into its finer distinguishable details, pairwise comparison judgements managed to capture the reality on the ground for ease understanding in order to aid decision making process. The strength of AHP in measuring consistency or lack thereof, improved the authenticity of the results of this study. For each hierarchical level of criteria and classes, the consistency ratios were acceptable ($\leq$ 10%) as proposed by Saaty (1977; 2012).

3.3. Validation of classification results

The validity of the results of the classification was verified using regression analysis of measured maize grain yield and land suitability indices (Figure 6). All regressions coefficients were significant, indicating that land suitability is directly linked to maize yield. The coefficients of determination (R^2) ranged from 63 to 85%. The correlations between grain yields and suitability classes is critical in placement of varieties of different maturity groups. Obtaining high yield in maize is largely a matter of matching land capability with varieties of suitable maturities. In most parts of Zimbabwe, rainfall, temperature, soil type and slope gradient are the major determinant factors. The correlation analyses confirmed the accuracy of the classification and showed good agreement between ranked land suitability classes and maize yield, which is a measure of genotypic adaptation.

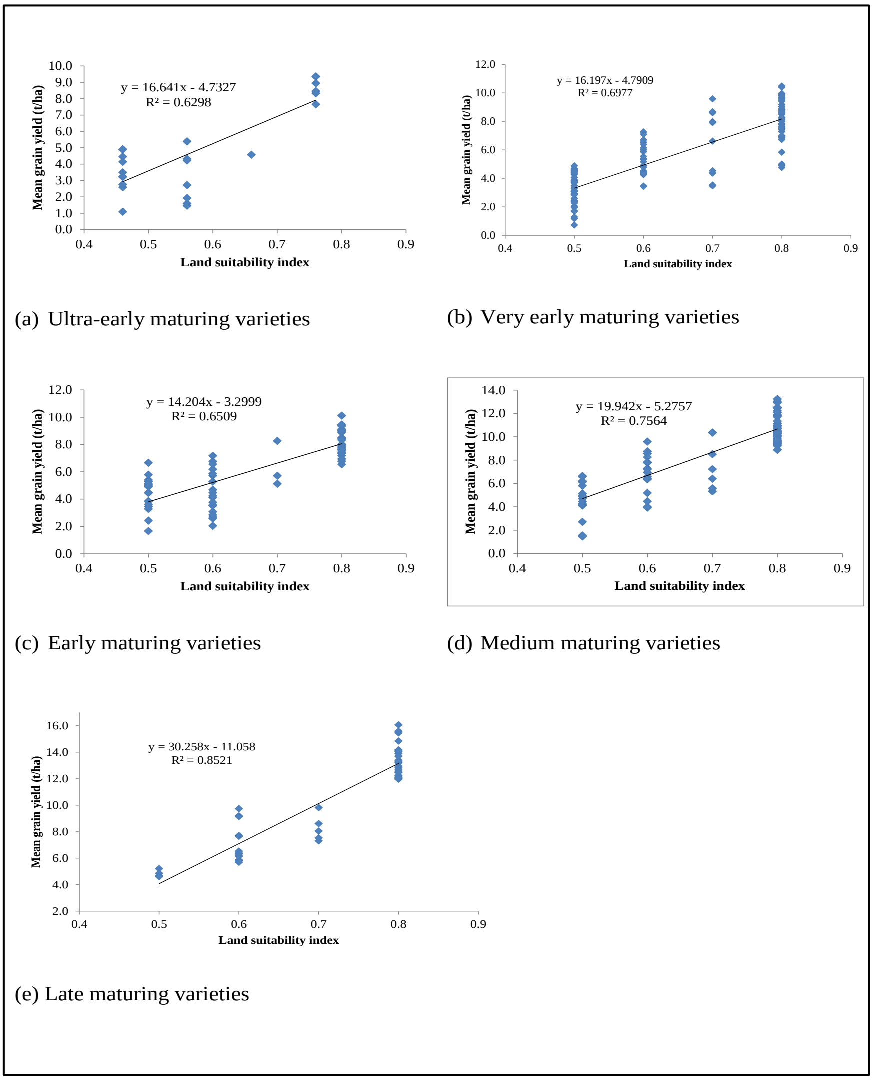


Figure 6. Regression analysis of maize grain yield vs land suitability index (a) late, (b) medium, (c) early, (d) very early, and (e) ultra-early maturing maize varieties

Integrating GIS and AHP was effective in producing land suitability map. However, empirically-derived quantitative information is needed to validate the classification (Van Lanen and Bouma 1989, Rossiter 1990). Validation of land suitability classification was performed using empirically-derived crop yield response from multi-environmental trials conducted in each land suitability class as recommended by Huajun and Van Ranst (1992). The high correlation (R^2 = 0.63 - 0.85) obtained between maize yield and suitability indices reflect the accuracy of the classification, confirming the effectiveness of combining GIS and AHP in land suitability assessment. Literature also confirms good correlation between land suitability indices and crop yield (Braimoh *et al*. 2004; Keshavarzi *et al*. 2010). The results also agree with findings by Akıncı *et al*. (2013), Feizizadeh and Blaschke (2013), Zhang *et al*. (2015), Mendas and Delali 92012) and Braimoh *et al*. (2004) who demonstrated the utility of integrating GIS and AHP in a MCE process in land suitability analysis.

Therefore, GIS-based land suitability analysis convert data into information that transform and adds value to the original data, which in its original form may not be useful for decision support system. GIS-based land suitability analysis has ability to incorporate both hard (physical environmental factors) and soft (expert knowledge) data into new information in the form of single suitability map (Carver 1991, Malczewski 2004). Hence, when integrated with AHP in a MCE process, GIS transforms and combines geographical data and value judgements into decision support information (Malczewski 2006a; 2006b).

4. Conclusion

From the results, we conclude:

- Integrating GIS and AHP with computer-captured expert knowledge was useful as a decision support tool in land suitability classification and mapping for maize production;
- The integration allowed us to manage the factors, create thematic layers, compute criterion weights, combine decision criteria through modelling, perform validation analyses and the production of maize suitability map needed for spatial decision-making support in maize crop placement;
- Significant positive correlation between maize yield and suitability indices is an indication that land suitability is directly linked to maize yield in the study area;
- AHP is a powerful method that is able to deal with inconsistent judgements and provides a measure of the inconsistency.

The maize suitability map can serve as a basis for decision support tool for policy makers, land-use planners and farmers alike regarding maize production in Zimbabwe.

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