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Original Research

Physical Models in Land Suitability Evaluation and Mapping for Surface Irrigation in Eastern Ethiopia

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Abstract

Land suitability evaluation is a system used to allocate land for appropriate use. The study examined the physical suitability of land for surface irrigation. Suitability of different land quality parameters viz. slope, soil texture, depth, erosion, drainage, soil pH, electrical conductivity (EC), organic matter (OM), total nitrogen (N), available phosphorus (P), cation exchange capacity (CEC), available water content, and infiltration rate were evaluated for irrigated crop production using physical models. The degrees of suitability of the area for the target land use were mapped using Arc GIS 10.1 Software. Based on soil variability across the landscape, 12 land mapping units (LMUs) were investigated. The study results showed that LMU2, LMU3 and LMU9 were classified under highly suitable (S1) category for surface irrigation. The LMU12 was found to be permanently not suitable (N2) for surface irrigation because of physical limitations. Major portion of the study site (37.55%) was highly suitable (S1) for surface irrigation. We found that LMU7 and LMU10 were highly suitable for maize (*Zea mays*), tomato (*Solanum lycopersicum*), green pepper (*Capsicum annuum*), and onion (*Allium cepa*). Our findings showed that the area is highly suitable for tomato but less suitable for maize production compared to other proposed crops. Finally, further research on socio-economic impacts of the proposed land use and identification of appropriate land improvement measures need to be undertaken.

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INTRODUCTION

The agriculture industry in Ethiopia is traditionally subsistence, which frequently suffers from rainfall variability (Seleshi & Camberlin, 2006). The high dependency on rain-fed farming in the dry-lands of Ethiopia and the erratic nature of the rainfall contributed to frequent food shortages throughout the country. The rainfall distribution and intensity vary spatially, tending to decrease from southwest to northeast (Cheung *et al*., 2008). These rainfall patterns affect crop production and contribute to volatility in food prices, which ultimately affects overall economic development (FAO, 2005). In the agricultural development strategy of the nation, irrigation development becomes an essential component of the food security for improving agricultural productivity, particularly in food insecure areas. Ethiopia has immense potential for expanding irrigated agriculture (Negash & Seleshie, 2004) as the country possesses high surface water potential from its twelve major river basins (Awulachew *et al*., 2007). The degree of land suitability for surface irrigation in Ethiopia varies spatially and temporally (Worqlul *et al*., 2015).

Land suitability refers to the ability of a portion of land to tolerate the production of crops in a sustainable way. Land could be categorized into spatially distributed agriculture potential zones based on the soil properties, terrain characteristics and analyzing present land use (Bandyopadhyay *et al*., 2009). Detailed survey information of land, water, and soil properties is essential for initiating land suitability evaluation and generating a land suitability map of a given region. Assessment of land and soil potential for irrigation include slope, topsoil texture, surface stoniness, rockiness, soil depth, soil pH, lime ($CaCO_3$) content, electric conductivity (EC), exchangeable sodium percentage (ESP), available P, total N and CEC (Sys *et al*., 1991). Remote sensing and GIS are used for interpolation and mapping of land units in accordance with their similarity and difference (Rao *et al*., 1996 and Panigrahy *et al*., 2006). It is used to map the land suitability classes for surface irrigation.

Expansion of irrigated land regardless of irrigation suitability assessment is becoming a great threat to natural resource base in Ethiopia. Land users are expanding small scale irrigation projects without prior scientific land suitability analysis leading to inappropriate land uses. To develop new irrigation schemes, land suitability evaluation is a prerequisite. Therefore, the main objectives of this research were to assess the degrees of suitability of the study site for surface irrigation, evaluate the suitability of the area for major proposed crops and develop suitability map at 1:10,000 resolution. This baseline suitability map will be useful for land users and planners working on development of surface irrigation schemes.

MATERIALS AND METHODS

Study Site

The study site, Gololcha, was located in Miesso district of west Hararghe Zone of the Oromia Region in eastern Ethiopia between $8^0$53’33’’ and $8^0$56’0.2’’ latitude and $40^0$18’30’’ and $40^0$53’33’’ longitude within altitudinal range of 1150 to 1240 m a.s.l. The mean annual rainfall of the study site was 785.7 mm. The mean monthly minimum and maximum temperature in the area were 18 ^{0}C to 21 ^{0}C, respectively. According to FAO (2014) soil classification legend, the major soils identified in the area were Fluvisols, Vertisols, Cambisols and Leptosols. The major geological formations of the site are Alaje formation, mainly consisting flood basalts associated with Trachyte (ignimbrites) and subordinate Trachyte forms - the bulk of the volcanic succession. The study site covers a total of 538.54 ha. Communities residing in the study area practiced mixed farming system. The major crops grown include maize (*Zea mays),* onion (*Allium cepa*), green pepper (*Capsicum annuum*), tomato (*Solanum lycopersicum*), and sorghum (*Sorghum bicolor*).

Characterization and Mapping of Land Units

In this study, a topographic maps of 1:50,000 scale, 30 m resolution LANDSAT ETM+ image, Google earth image and digital elevation models (DEM) were overlaid to produce a base map. During land suitability evaluation, land and soil characteristics such as slope, soil texture, soil depth, drainage, EC, soil pH, carbonate content, cation exchange capacity (CEC), organic matter (OM), total nitrogen (N), and available phosphorous (P) were considered (Sys *et al*., 1991); and analyzed following standard laboratory procedures. For laboratory analysis, nearly 41 composite soil samples were collected from genetic horizons of 15 profile pits that were also described in the field following FAO (2014) soil description guideline. Infiltration rate was tested by using double-ring infiltrometer. Other surface conditions viz. surface stoniness, erosion status, and flood hazard were also evaluated in the field using transect surveys. Finally, based on soil-landscape variations, land mapping units (LMUs) were produced using Arc GIS 10.1 software.

The physical suitability evaluation for surface irrigation was carried out following FAO method for general irrigation farming (FAO, 1997). The suitability classification was carried out by matching soil quality parameters of each land mapping unit with class determining factors (Resler, 1979). Land quality parameters were compared with critical values used as a class determining factors (Table 1) to develop land suitability class. Finally, suitability of the study site for surface irrigation in general and major proposed irrigated crops including maize (*Zea mays*), green pepper (*Capsicum annuum*), onion (*Allium cepa*) and tomato (*Solanum lycopersicum*) in particular were mapped using ArcGIS 10.1 software.

Suitability Analysis and Mapping Methods

Table 1: Land use requirement and critical class limits for surface irrigation (Resler, 1979)

Class determining factors	Suitability class rating			
	S1	S2	S3	N
Slopes (%)	0 – 2	2-5	5-8	>8
Drainage	W, MW	I	P	VP
Depth (cm)	>100	80-100	50-80	<50
Soil texture	L-SICL,C	SL	-	-
Structure	SAB	SAB	Platy	Massive
Salinity- EC (ds/m)	<8	8-16	16-24	>24
ESP (%)	<15	15-30	30-45	>45
CEC (meq/100 g)	>20	5-20	1-5	<1
OM (%)	3-5	1-3	<1	<1
Total N (%)	>0.5	0.2-0.5	0.1-0.2	<0.1
Available P (ppm)	>15	5-15	2-5	<2
C/N	10-12	6-10	<6	<6-
pH	5.5-7	5-5.5 & 7-8	4.5-5 & 8-8.5	<4.5 & >8.5
IR (cm/hr)	0.5-3.5	0.1-0.5	6.5-10.0	<0.1, >10
AWC (mm/m)	>150	100-150	75-100	<75

S1: highly suitable, S2: moderately suitable, S3: marginally suitable, N: not suitable, EC: electrical conductivity, IR: infiltration rate, AWC: available water content, W: well, MW: medium to well, I: intermediate, P: poor, VP: very poor

Statistical Analysis

A measured and average value of each variable was compared with its critical values. Descriptive statistics was used to illustrate mean and percentage of the measured variables (land quality parameters). Geo-statistical tools were used to estimate probability distribution of land mapping units and aerial coverage of the land units. Analyzed data was presented in Tables and Figures.

RESULTS AND DISCUSSION

Land Mapping Units and their Characteristics

Land characteristics greatly vary spatially and govern distribution of LMUs. Excluding the rock surface, 12 LMUs were identified in the study site on the basis of land use, topographic and soil variables (Figure 1a). The largest portion (12.29%) of the total study site was constituted by LMU3 while the smallest portion (2.78%) was occupied by the SMU12.

Table 2: Characteristics and qualities of the land mapping units

Land quality parameter	Land mapping units											
	LMU1	LMU2	LMU3	LMU4	LMU5	LMU6	LMU7	LMU8	LMU9	LMU10	LMU11	LMU12
Slope (%)	2-5	0-2	2-5	0.2	0-2	2-5	2-5	2-5	5-8	8-15	8-15	15-30
Depth (cm)	>100	50-80	80-100	>100	50-80	50-80	50-80	80-100	>100	80-100	80-100	<25
pH (1:2.5)	7.65	7.29	7.80	8.03	7.72	8.65	7.56	7.89	8.44	7.47	7.58	7.42
EC (ds/m)	0.17	0.19	0.25	0.21	0.28	0.17	0.11	0.16	0.23	0.22	0.22	0.27
Texture	CL	L	CL	CL	C	SCL	CL	C	CL	CL	C	L
CEC (Cmol(+)Kg-1)	48.40	52.40	50.80	52.40	53.40	52.00	53.40	50.40	56.52	48.40	53.40	42.40
TN (%)	0.15	0.13	0.24	0.18	0.14	0.20	0.08	0.15	0.13	0.14	0.15	0.21
OC (%)	1.39	1.52	2.43	2.24	1.40	1.93	0.98	1.54	1.36	1.55	1.75	1.43
C:N ratio	9.24	11.67	10.13	12.43	10.01	9.65	12.29	10.27	10.49	11.49	11.67	6.81
Av.P (ppm)	5.34	3.80	1.14	4.80	1.80	2.24	1.70	2.60	1.28	2.60	2.08	2.54
$CaCO_3$ (%)	2.52	22.97	11.04	3.06	5.22	5.65	6.66	15.95	1.93	4.75	3.78	7.02
IR (cm/hr)	0.40	2.20	0.50	0.35	0.50	6.56	4.80	0.50	3.20	3.40	2.80	0.25
AWC (mm/m)	146	187	206	138	184	93	123	160	201	158	179	132

CL: clay loam, L: loam, C: clay, SCL: sandy clay loam

Land quality parameters showed variations across the LMUs resulting in unequal suitability of the land units for surface irrigation. The slope steepness of land mapping unit 12 was so high (15-30%) that soil depth was too shallow (Table 2). According to Resler (1979), soil depth varied from shallow (< 50 cm), moderate deep (50–80 cm), deep (80–100 cm) to very deep (>100 cm). Based on this depth category, soils of LMU12 were shallow. Particle size analysis result showed that LMU1, LMU10, LMU4, LMU7, LMU9 and LMU3 were texturally dominated by clay loam whereas LMU5, LMU11, and LMU8 were dominated by clay soils. Soils of the remaining land units were loam (Table 2). The soil pH ranged from 7.29 to 8.65. This indicated that the soils were slightly alkaline since the pH was higher than the preferred pH range (5.8-7.5) for most commercial crops as recommended by Retamales and Hancock (2012). The overall organic carbon (OC) content of the soils ranged from 0.98 to 2.43%, which could be rated as very low to low based on Landon (2014). Moreover, exchangeable basic cations, CEC, percent base saturation (PBS), and $CaCO_3$ content of soils in the study site were relatively higher (Table 2). This shows that the soils were highly susceptible to salinity problems unless and otherwise immediate corrective measures were undertaken during application of irrigation water and other chemical inputs.

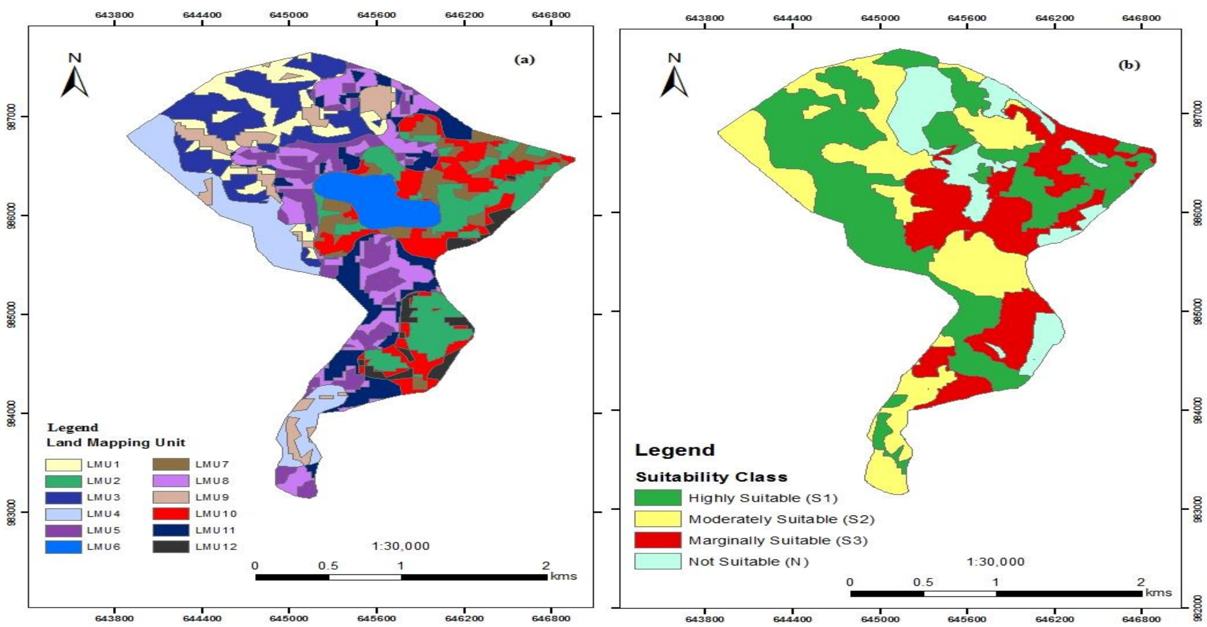

Figure 1: The (a) land mapping units of the study site and (b) surface irrigation suitability map

Physical Land Suitability for Surface Irrigation

Matching and superimposing of the land use requirements and critical class limits with the land quality parameters in each LMU were resulted in suitability classes. Initially, the matching was performed between each land quality parameter (Table 2) and its critical limits (Table 1) in all land units; and thus these individual ratings were combined to give an overall suitability class for the land units (Table 3). Land and soil quality parameters or factors were found to either slightly, moderately or severely limit irrigated crop production depending on the category of the land units. According to FAO (1985 & 2007) land suitability classification systems, soils of the study area could be classified into four suitability classes-S1, S2, S3 and N (Figure 1b and Table 3) recognized within two orders (suitable-S and not suitable-N). Based on the same systems of classification, land suitability subclasses could be identified as shown in Table 3.

Table 3: Results of surface irrigation suitability classification

Land mapping units	Suitability class	Suitability sub-class
LMU1	S2	S2e
LMU2	S1	S1
LMU3	S1	S1
LMU4	S2	S2t,a
LMU5	S2	S2e,t,r
LMU6	S3	S3e,a
LMU7	S3	S3e,a
LMU8	S2	S2t,r
LMU9	S1	S1
LMU10	S3	S3e
LMU11	S3	S3e
LMU12	N2	N2

E: erosion, t: topography, a: alkalinity, r: rock surface, N2: permanently not suitable

From all land units investigated, LMU2, LMU3 and LMU9 were classified under S1 (highly suitable for surface irrigation). This implied that these three land units have no significant limitations to sustained irrigated crop production (application of surface irrigation), or only minor limitations that will not significantly reduce productivity or benefits obtained from the land and will not raise inputs above an acceptable level. Those three land units have had only slight limitations of soil pH, total N, and available P. Meanwhile, LMU1, LMU4, LMU5, and LMU8 were found to be moderately suitable (S2) for irrigated crop production. The land units were moderately limited by slope, soil texture, soil depth, and OM; however, special attention should be given to soil alkalinity, total N, and available P. The limitations will reduce productivity or benefits obtained from the land and increase the required inputs to the extent that the overall advantage to be gained from the use. Similarly, LMU6, LMU7, LMU10, and LMU11 were identified to be marginally suitable (S3) because they have severe limitations of most land use requirements (land quality parameters) for sustained irrigated crop production.

The impact of land quality parameters presented in Table 2 in reducing the suitability of a land for irrigated crop production was reported by Mohamed *et al*. (2016). Alkalinity was reported as main limiting factors for irrigation suitability, not only in the present study site but also elsewhere across the world (Teshome *et al*., 2016). Special consideration should be taken while developing irrigation schemes on land units when their slope rises above 8%. According to Turner and Scotney (1993), slopes less than approximately 8% are generally considered as suitable for irrigation development. This might be due to soil loss by erosion on slopes greater than 8% was too high. Steeply areas should be assisted by soil and water conservation works to reduce soil loss and apply integrated soil fertility management practices to reverse the nutrients depleted by erosion. The LMU12 was found to be unsuitable (N2) for surface irrigation because of physical reasons. The soils of LMU12 had high slope steepness, very shallow depth (<25 cm) and deficit in major nutrients. The marginality of shallow soils to crop production was reported by Mishra and Sahu (1991).

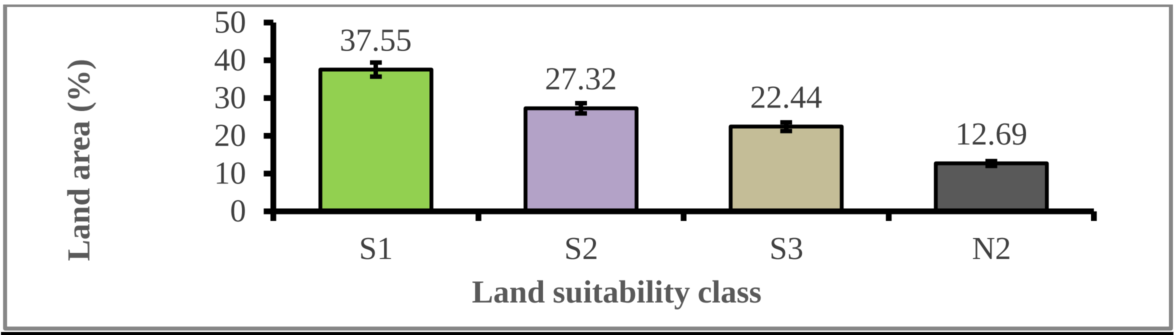

Figure 2: Proportion of the total study area covered by different land suitability classes

The results showed that major portion of the study site (37.55%) was highly suitable (S1) for surface irrigation (Figure 2). Nearly 22.44% of the entire study area was classified as marginally suitable (S3) and requires major land improvement measures if its use for surface irrigation has no alternative option. But one needs to understand that marginal suitability of 22.44% of the study site for surface irrigation did not mean that it was also marginally suitable for other uses. Land suitability is relative and it might be highly suitable for other uses such as forestry or grazing land. Meanwhile, 12.69% of the study area was permanently not suitable (N2) for surface irrigation.

Land Suitability for Selected Crops

Crops were selected based on existing conditions, climate, and requirement of individual crops for daily consumption and income generation for the community. The major proposed crops were maize (*Zea mays*), onion (*Allium cepa*), pepper (*Capsicum annuum*) and tomato (*Solanum lycopersicum*). Matching and superimposing crop requirements under irrigation with soil qualities and limitations, we produced an irrigated crop suitability class for each LMU.

Table 4: Land/soil mapping units' suitability class for proposed irrigated crops

Land mapping units	Proposed crops			
	Maize	Onion	Tomato	Pepper
LMU1	S3	S1	S2	S2
LMU2	S2	S3	S1	S3
LMU3	S3	S3	S2	S1
LMU4	S3	S2	S1	S2
LMU5	S3	S2	S1	S2
LMU6	S2	S3	S2	S3
LMU7	S2	S1	S1	S1
LMU8	S3	S1	S1	S2
LMU9	S2	S3	S2	S3
LMU10	S2	S1	S1	S1
LMU11	S3	S1	S2	S1
LMU12	N2	N2	N2	N2

Table 5: Land area under different suitability classess for the major crops

Land suitability class	Percentage of area			
	Maize	Onion	Tomato	Pepper
Highly suitable (S1)	0.00	34.30	46.83	37.44
Moderately suitable (S2)	38.41	11.78	41.10	27.51
Marginally suitable (S3)	49.53	41.86	2.33	22.98
Permanently not suitable(N2)	12.07	12.07	9.74	12.07

Accordingly, LMU1, LMU7, LMU8, LMU10, and LMU11 were highly suitable for irrigated onion (*Allium cepa*) production while LMU3, LMU7, LMU10, and LMU11 were highly suitable for irrigated pepper (*Capsicum annuum*) production (Table 4). From all land units, LMU7 and LMU10 were highly suitable for all crops in question. Overall suitability inspection revealed that the degree of suitability of the site for the proposed crops was in order of tomato (*Solanum lycopersicum*)> pepper (*Capsicum* annuum) > onion (*Allium cepa*) > maize *Zea mays*) (Table 5). The objective of various soil evaluation studies was to predict and classify the land for plant growth (Sehgal, 1996).

The land suitability assessment for maize showed that nearly 38.41% of the study site was moderately suitable and nearly 49.53% was marginally suitable (Table 5). Maize (*Zea mays*) was the most important grain crop in Ethiopia. It can be grown on a wide variety of soils, but performs best on well-drained, deep warm loams and silt loams containing adequate OM and available nutrients (Alemayehu *et al*., 2011). Maize (*Zea mays*) grows best in soil with a pH between 5.8 and 6.8 (Howard *et al*., 2003). Outside this pH range, there is nutrient deficiency and mineral toxicity. Knowing this guide, the main constraints to maize (*Zea mays*) production in the area were eroded soils, clayey dominated soils, alkalinity (soil pH > 7.29), deficiency of N and P nutrients, erratic rainfall, and low OM. Unless improvement measures are undertaken, currently all land units could not be classified as highly suitable (S1) for irrigated maize (*Zea mays*) production (Figure 3a).

The suitability evaluation for onion (*Allium cepa*) indicated that nearly 34.30% of the study site was highly suitable and nearly 11.78% was moderately suitable for onion (*Allium cepa*) production (Table 5). Onion (*Allium cepa*) was considered as one of the most important vegetable crops produced on large scale in Ethiopia. It prefers fertile sandy loam and loam soils well supplied with OM. A soil pH of 6.0-8.0 is preferred for onion production (Olani & Fikre, 2010). They have shallow and limited root systems which explore mainly the upper 30 cm of the soil. Except overall deficiency of soil nutrients, the area could be suitable for onion (*Allium cepa*) production compared to maize (*Zea mays*) production (Figure 3b).

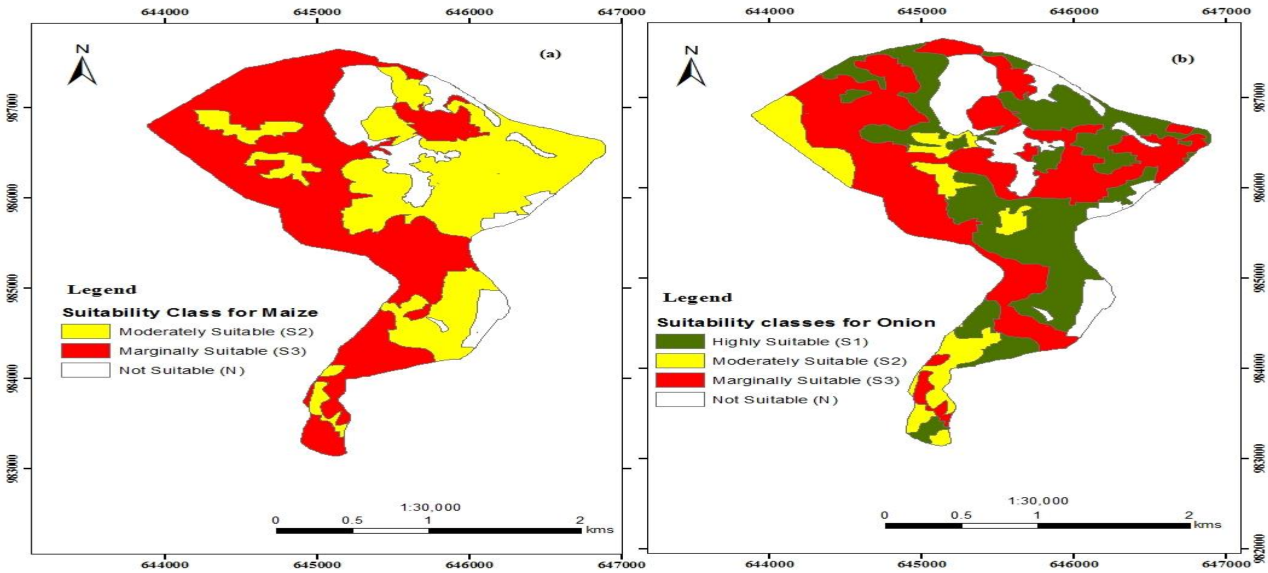

Figure 3: Land suitability map for irrigated (a) maize (*Zea mays*) and (b) onion (*Allium cepa*) production

Our results indicated that the study site was well suited for irrigated tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) production compared to other proposed crops (Figure 4a and 4b). The suitability evaluation for tomato (*Solanum lycopersicum*) revealed that nearly 46.83% of the study site was highly suitable and nearly 41.10% was moderately suitable (Table 5). This implied that a total of 87.93% of the total study area was suitable for tomato (*Solanum lycopersicum*) production. Besides, land suitability assessment for pepper (*Capsicum annuum*) showed that about 37.44% of the area was highly suitable while 27.51% was moderately suitable for the crop. With slight investment on correction of limiting factors, the degree of suitability of the site for tomato (*Solanum lycopersicum*) and pepper (*Capsicum annuum*) production can be increased.

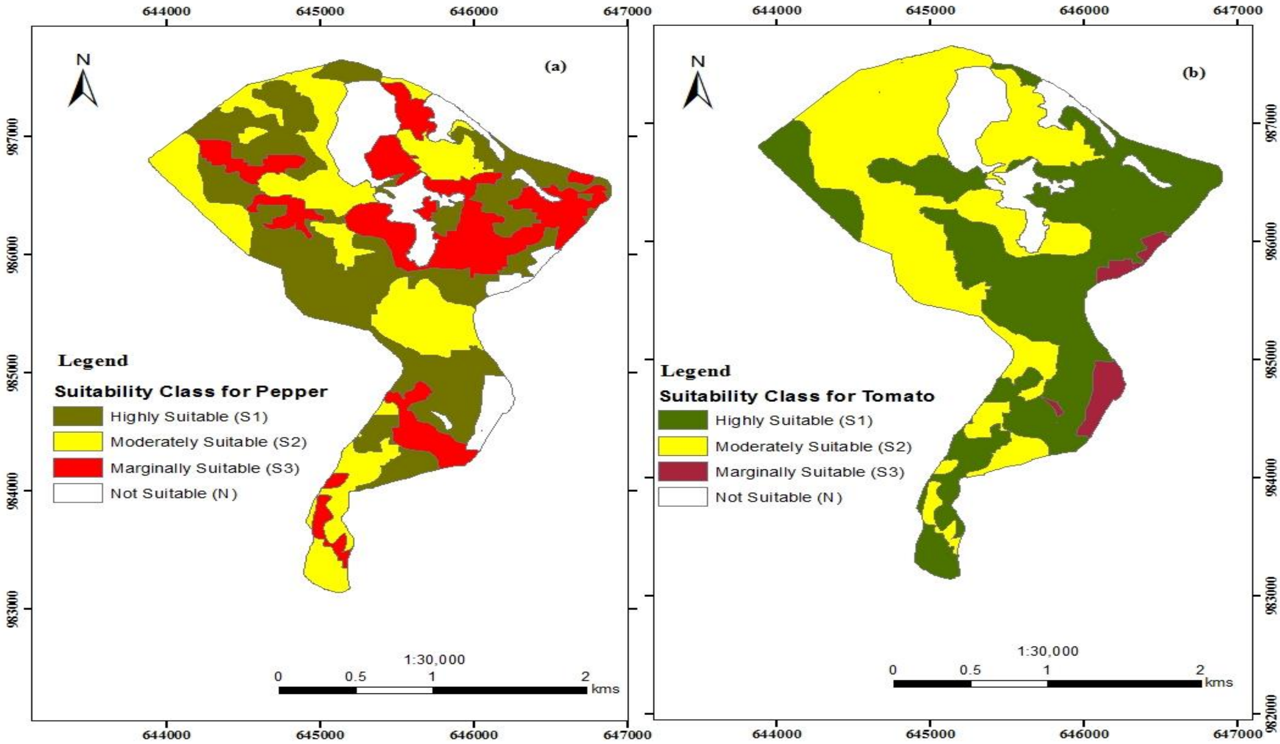

Figure 4: Land suitability map for irrigated (a) pepper (*Capsicum annuum*) and (b) tomato (*Solanum lycopersicum*) production

Management Requirements

The suitability class of each land units for the crops in question can be upgraded by undertaking some land improvement measures. Each LMU had its own limitations and potentials. For instance, LMU1 was marginally suitable for irrigated maize (*Zea mays*) production but moderately suitable for tomato (*Solanum lycopersicum*) and pepper (*Capsicum* cayenne) productions (Table 4). Therefore, it is possible to upgrade the suitability class of LMU1 from marginally suitable (S3) to either moderately suitable (S2) or highly suitable (S1) for irrigated maize (*Zea mays*). Besides, it could be possible to improve suitability class of LMU1 for tomato (*Solanum lycopersicum*) and pepper (*Capsicum* cayenne) production from moderately suitable to highly suitable class. Land management measures are usually implemented only if cost of rehabilitation is less than the benefits obtained from crop produce.

In the present study site, the dominant limiting factors observed in most LMUs were slope, soil depth, soil texture, alkalinity (soil pH), total N and available P. Land units having limitations of slope could be improved by land leveling or applying soil and water conservation measures. The farmers experience in different areas showed that moderately steep lands were developed under different irrigation techniques with adequate conservation practices. Nethononda *et al*. (2014) reported that the intensity of conservation measures in the form of terracing increases with increasing percent slope. On shallow soils, shallow rooted crops can be best alternative. The calcium carbonate ($CaCO_3$) content of the soils in the study area ranged from 1.93 to 22. 97% with an average value of 6.30 %, and rated as high level. In calcareous soils, application of acid forming amendments such as sulfur could be more effective. Excessive amount of carbonate restricts root development and induces available phosphorous, iron and micronutrient deficiencies. When phosphorus status of the soil is very low, the application of phosphate fertilizers is crucial to raise P status of the soil to optimal level for crop production (Nethononda *et al*., 2014). Phosphorous deficiency in the soil is improved by application of phosphorus containing chemical fertilizers and addition of animal manures. Low level of nitrogen in the soil can be amended by addition of nitrogen containing chemical fertilizers, bio-fertilizers, growing legumes, addition of green and animal manures. Split application of N might be appropriate strategy to deal with such a challenge to ensure constant supply of this nutrient element during different stages of crop growth (Van Averbeke *et al*., 2007). In alkaline soils, use of Urea fertilizer has two advantages namely, as source of nitrogen nutrient and source of hydrogen (H^+) that helps to decrease soil pH (reduce soil alkalinity). Generally, the concept of upgrading land suitability class for a defined use would be applied only if the cost associated with land improvement measures seems to be less than the benefits obtained due to upgrading operations.

CONCLUSIONS AND RECOMMENDATIONS

Detail information on soils and other land characteristics provide a basis for decision making on proper utilization and management of land resources. Variability of land quality parameters across the landscape was the basis for classifying the study area into LMUs. This variability was resulted in unequal suitability of the land units for a defined use. The most dominant limiting factors in soils of the study site were high slope gradient, soil texture and shallow soil depth. These were the major factors affecting suitability of the area for surface irrigation. We understood that major portions of the area were highly to moderately suitable for surface irrigation. Moreover, we concluded that the area was highly suitable for tomato but less suitable for maize production compared to other proposed crops. It can be possible to improve the degree of suitability of the land for a given land use type. In areas where surface irrigation was not highly suitable because of slope steepness, it could be possible to apply soil and water conservation interventions such as soil bunds and bench terracing to upgrade the suitability class of the land. In areas where deficiency of soil nutrients were the major limiting factors affecting suitability, integrated soil fertility management practices would be used to upgrade the suitability of the soil. Owing to scarcity of land resources compared to the ever increasing demand, land suitability improvement measures can be recommended if the cost of upgrading the land is less than the forecasted benefits that could be obtained from the land.

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