

Full Length Research Paper

Land suitability evaluation for rainfed production of barley and wheat at Kabe Subwatershed, Northeastern Ethiopia

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In developing countries, where resources are often scarce, land availability, productivity potential, capability and sustainability for agriculture and, planning and maximizing the use of the land resources for a particular land utilization type is essential. In order to ensure appropriate decision and, continued and sustainable productivity, thereby continuing to support the population economically without degradation, scientific and proper evaluation is essential. In view of this, land suitability evaluation was carried out for rainfed production of barley and wheat at Kabe Subwatershed. Maximum limitation method was applied for determination of the suitability classes of land characteristics. Results of the ultimate suitability evaluation showed that 9.93% of the study area is marginally suitable (S3) and 38.68% is currently unsuitable (N1) for both spring barley and wheat production under subsistence rainfed agriculture. On the other hand, 51.39% of the study area is permanently unsuitable (N2) for spring wheat production but currently unsuitable (N1) for spring barley production. The potential suitability evaluation remain the same due to permanent limitations related to consistence and slope steepness although the others can be corrected and improved. The limiting but correctable soil and landscape characteristics for the optimum production of the crops evaluated should be corrected or improved based on the level of management.

Key words: land evaluation, physical suitability, maximum limitation, rainfed agriculture.

INTRODUCTION

Land evaluation is the process of assessing land performance when the land is used for specified purposes under a stated system of management and involves the execution and interpretation of surveys and studies of landforms, soils, climate, vegetation and other aspects of land in order to identify and compare promising kinds of land use in terms applicable to the objectives of the evaluation (Sys et al., 1991a, b; Davidson, 1992; FAO, 2007). The suitability is a function

of crop requirements and land characteristics and it is a measure of how well the qualities of land unit match the requirements of a particular form of land use (FAO, 1976).

Considering the rapid growth of the world populations, which is in its turn a limiting factor to the arable lands around the world, the dire need for effective and efficient application of croplands have been felt more than ever (Albaji et al., 2012). Suitability of land is assessed considering rational cropping system, for optimizing the use of a piece of land for a specific use (Sys et al., 1991a). Land evaluation is a vital link in the chain leading to sustainable management of land resources (FAO, 2007). The increased need for food production and the

shortage of resources stimulate a need for sophisticated methods of land evaluation to aid decision-makers in their role to both preserve highly suitable lands and satisfy producers' demands for increasing profits (Bagherzadeh and Daneshvar, 2011).

In order to meet the increasing demand for food, the farming community has to produce more and more. However, under the present situation, where land has become a limiting factor, it is impossible to bring more area under cultivation to satisfy the growing demand (Fischer *et al.*, 2002). Thus, for a successful agriculture to meet the increasing demands of food, fiber and fuel from the decreasing per capita land, requires sustainable use and increasing productivity per unit. An increase in agricultural production, particularly rainfed cropping, is a function of soil, climate and agro-technology. Ethiopia faces a wide set of issues due to limitation of rational information on land suitability evaluation and poor land use planning practices are putting serious strain on the land and its resources.

Generally, in Ethiopia, land availability, productivity potential, capability and sustainability for agriculture and, planning and maximizing the use of the land resources for a particular land utilization type is not adequately known. This has led to inappropriate decisions and for policy makers and decision makers make guidance and optimization difficult. Wollo, where the study area is situated, is one of the most severely degraded and low agricultural productivity parts of the Ethiopian highlands resulted from erosion and soil quality deterioration (Kebrom, 1999). Thus, proper evaluation of the land should be carried out in order to ensure continued and sustainable productivity, thereby continuing to support the population economically without degradation. Therefore, the main aim of this study is to evaluate physical land suitability for barley and wheat production under rainfed agriculture.

MATERIALS AND METHODS

Description of the Study Area

Geographically, the Kabe Subwatershed is found in Kebele 014, Wereillu District, South Wollo Zone of the Amhara Regional State (Figure 1), in the highlands of Abay (Nile) Basin. The geographical location of the study area lies between the UTM coordinates of 1197404 to 1200113 m north latitude and 548971 to 550728 m east longitude with an elevation that ranges from 2844 meters above sea level (masl) just near the Selgi River to 3172 masl at the top of the Subwatershed. The topography of the area is not uniform and most part is characterized by hilly and steeply dissected topography with moderately steep to steep slopes.

Ethiopian National Meteorology Authority, Kabe-Wollo Station, indicates that the mean annual rainfall of the area is about 866.5 mm and the maximum amount of rainfall is observed in the month of July followed by August. Based on 21 years climate data (1992-2012), the mean minimum and maximum annual air temperatures of the area are 8.6 and 19.1 °C, respectively, with mean annual air temperature of 13.9 °C with the warmer month occurring in June and colder in November. Based on length of growing period, the agro-ecological zone (AEZ) of the area is classified as cool to

tepid moist mid highlands (*dega*) (EIAR, 2011). The major geologic parent materials of the area are Cenozoic volcanic rocks particularly Tarmaber-Megezez formations (transitional and alkaline basalts) (Tefera *et al.*, 1996). Mixed livestock and crop production is the major farming system in the study area.

According to FAO (1984), the soils of Wollo area have been developed almost exclusively on Trap Series volcanoes. The soils on the land forms, which include wide parallel valleys, side slopes and volcanic plateaux, are generally stony phase eutric and dystic Vertisols or vertic Cambisols. In the intensively cultivated, even on minimum slopes, these highly erodible soils can become quite shallow. On the steeper land forms, eutric Cambisols predominate, with lithic phases and Leptosols occurring on the steepest slopes.

Description of Soil Mapping Units

Soil Mapping Unit SMU1

The soil mapping unit was represented by soil Pedon 1. It has steeply dissected topography with slope of 33%, shallow effective soil depth (25 cm), strongly eroded area and drained soil, color ranged from reddish yellow (7.5YR 6/6) to yellowish brown (10YR5/4) when dry and from yellowish brown (10YR 5/6) to brown (7.5YR 4/3) when moist, weak medium granular to moderate medium sub-angular prismatic structure, slightly hard to hard (dry), friable to very friable (moist) and sticky-slightly plastic to slightly sticky-slightly plastic (wet) consistency, no excessive compaction and restriction of root development, and sandy clay loam in texture throughout. The mapping unit was slightly acidic in pH (6.11-6.24), free from salinity ($< 1\text{dsm}^{-1}$), low in OM (0.90-1.31%) content, very low in total N (0.03-0.05%) content, low in available P (14.90-16.90 mgkg^{-1}) content, exchangeable Ca (14.25-15.42 cmol (+) kg^{-1}) and Mg (5.07-6.17 cmol (+) kg^{-1}) dominated exchange complex, high in divalent (Ca and Mg) and moderate in monovalent (Na and K) exchangeable basic cations, high CEC (27.40-29.20 cmol (+) kg^{-1}), high PBS (73.92-77.09%) and general high status of micronutrients (Fe, Mn, Cu and Zn).

Soil Mapping Unit SMU2

The soil mapping unit was represented by soil Pedon 2. It has slope of 23%, moderately deep effective soil depth (100 cm), well drained, color ranged from dark reddish gray (2.5YR 4/1) to reddish brown (2.5YR4/3) when dry and from dark reddish gray (2.5YR 3/1) to reddish brown (5YR 4/3) when moist, weak fine granular to moderate to strong medium angular blocky structure, slightly hard throughout (dry), loose to very friable (moist) and slightly sticky-non plastic to sticky-slightly plastic (wet) consistency, no excessive compaction and restriction of root development, and sandy loam to sandy clay loam in texture. The mapping unit was slightly acidic in pH (6.15-6.27), free from salinity ($< 1\text{dsm}^{-1}$), low in OM (1.51-2.08%) content, low in total N (0.08-0.09%) content, very high available P (37.73-42.49 mgkg^{-1}) content, exchangeable Ca (10.95-12.33 cmol (+) kg^{-1}) and Mg

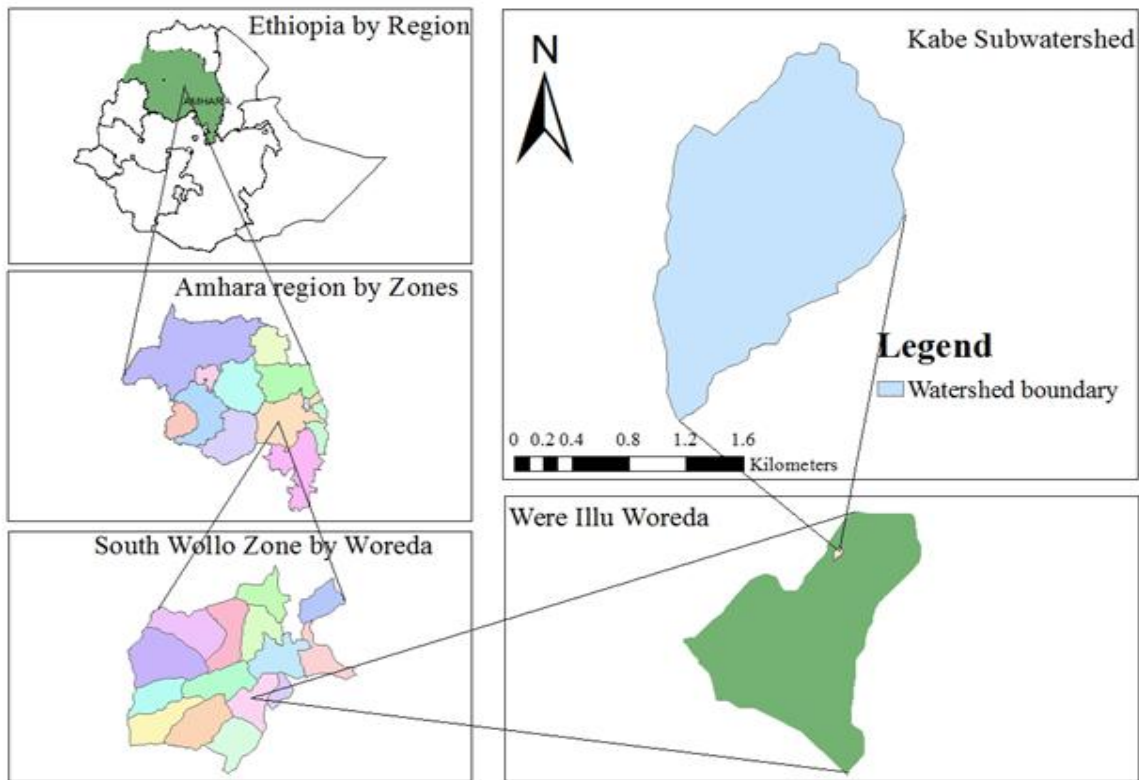


Figure 1. Location map of the Kabe Subwatershed.

(3.96-4.69 cmol (+) kg^{-1}) dominated exchange complex, high in divalent (Ca and Mg) and moderate in monovalent (Na and K) exchangeable basic cations, high CEC (23.40-29.80 cmol (+) kg^{-1}), high PBS (59.50-69.77%) and general high status of micronutrients (Fe, Mn, Cu and Zn).

Soil Mapping Unit SMU3

The soil mapping unit was represented by soil Pedon 3. It has slope of 20%, very deep effective soil depth (160 cm), moderately well-drained soil, color ranged from light brownish (10YR 6/2) to very dark gray (7.5YR3/1) when dry and from very dark gray (2.5Y 3/1) to reddish brown (5YR 4/3) when moist, moderate to strong coarse granular to strong medium sub-angular prismatic structure, soft to hard (dry), loose to firm (moist) and non sticky-non plastic to very sticky-plastic (wet) consistency, no excessive compaction and restriction of root development, and clayey to sandy clay loam in texture. The mapping unit was slightly acidic in pH (6.32-6.45), free from salinity ($< 1\text{dsm}^{-1}$), very low to low in OM (0.27-1.45%) and total N (0.01-0.09%) content, low to medium available P (9.0-17.65 mgkg^{-1}) content, exchangeable Ca

(10.54-14.60 cmol (+) kg^{-1}) and Mg (6.17-6.85 cmol (+) kg^{-1}) dominated exchange complex, high in divalent (Ca and Mg) and moderate in monovalent (Na and K) exchangeable basic cations, high CEC (27.00-34.00 cmol (+) kg^{-1}), moderate to very high PBS (59.30-81.57%) and general high status of micronutrients (Fe, Mn, Cu and Zn).

Soil Mapping Unit SMU4

This soil mapping unit was represented by soil Pedon 4 which was opened at relatively lower slope area (5.5%) than the others. It has deep effective soil depth (130 cm), alternate wet - dry expansion and swelling clays, cracks which open and close periodically, high activity clays, poor to imperfect drainage characteristics, color ranged from very dark gray (10YR 3/1) to grayish brown (10YR 5/2) when dry and from very dark gray (7.5Y 3/1) to dark reddish brown (5YR 3/2) when moist, moderate fine granular to strong coarse angular and sub-angular blocky structure, slightly hard to very hard (dry), friable to firm (moist), non sticky-non plastic to very sticky- very plastic (wet) consistency and clayey to sandy clay loam in texture. The mapping unit was slightly acidic in pH (6.22-6.42), free from salinity ($< 1\text{dsm}^{-1}$), very low to low in OM

(0.43-1.02%) and total N (0.01-0.08%) content, very low to medium available P (2.35-21.57 mgkg⁻¹) content, exchangeable Ca (16.28-19.77 cmol (+) kg⁻¹) and Mg (6.55-8.04 cmol (+) kg⁻¹) dominated exchange complex, high in divalent (Ca and Mg) and moderate in monovalent (Na and K) exchangeable basic cations, high to very high CEC (32.60-40.80 cmol (+) kg⁻¹) and PBS (62.17-83.23%) and general high status of micronutrients (Fe, Mn, Cu and Zn).

Land Suitability Evaluation procedures for Rainfed Crop Production

Selection of land qualities, characteristics and diagnostic criteria for suitability evaluation

The suitability evaluation for the crops was determined based on the procedures, which consisted of collection obtaining information (knowledge and data) on these attributes as outlined by FAO (1983).

Agro-climatic analysis

All the necessary climatic data for the suitability evaluation were obtained from the Ethiopian Meteorological Service Agency (EMSA) of Kombolcha branch. Records of 30 years rainfall, 21 years temperature, and 11 years wind speed, relative humidity and sunshine hours data were used. The 11 years duration restricted data of wind speed, relative humidity and sun shine hours were because of limited availability of data at the station and absence at nearby meteorological stations (Kabe, Gugufu and Wereillu). These climatic characteristics were used as input parameters for the computation of length of growing period (LGP), sowing date and selection of crop varieties. Average values of the data series of the climatic parameters were used for the computation of the LGP and average values for the LGP of selected parameters were calculated and used for suitability evaluation.

The computation of the reference evapotranspiration was made by FAO-Penman Monteith method using CropWAT version 8 program for windows (FAO, 2009). The start of the growing period and likely end of rains were determined using both graphical and linear interpolation techniques based on rainfall and evapotranspiration data as outlined by Sys *et al.* (1991a). Growing period starts when a rainfall amount is equal to or greater than half of the reference evapotranspiration (0.5ET_o) during the beginning of the rainy season and the end of the rainy seasons was set when the rainfall amount during the end of season is again less than half of the corresponding reference evapotranspiration (0.5ET_o). The same applies to the start and end of humid period but in reference to ET_o.

topography/landscape, climate and soil characteristics, and characterization of data on relevant crop data, descr-

ption of the land utilization types (LUTs), and determination of the requirements of the land utilization types. Land use requirements (LUR) of the selected LUTs were obtained through desk review of the existing publications and reports (Appendix Tables 1 and 2). These requirements are for rainfed agriculture and suitability evaluation was made by comparing the above characteristics against the requirements using the procedures outlined by FAO (1983) and Sys *et al.* (1991a).

Among the land qualities to be considered in land suitability evaluations, some of them were selected in this study (Tables 1 and 2). The land qualities, characteristics, and diagnostic properties were selected based on consideration of the known effects of these attributes on the crops, importance of the use, presence of critical values (adverse/favorable) and practicability of

Finally, the LGP was defined by counting the number of days between the start of the growing period and the end of rains plus the period required to evapotranspire the assumed 100 mm moisture stored in the soil reserve (time of soil moisture utilization) during the rainy season. The length of period (in days) required to evapotranspire the assumed 100 mm water stored in the soil at full rates of evapotranspiration was computed using the simple water balance method, which is the difference between rainfall and reference evapotranspiration (RF-ET_o). The computation of the water storage began with the first month of the humid season (RF > ET_o) as indicated in FAO (1983).

Characterization of soil and landscape

Soil suitability evaluation in this study consisted five main qualities: nutrient availability, nutrient retention, rooting conditions, soil workability and oxygen availability. Since the land suitability evaluation in the study area was for annual crops of barley and wheat, a reference depth of 100 cm was used. Since the soil horizons had different textural classes and coarse fragments, new textural classes and coarse fragments were calculated for the depth of the rooting zone for the representative pedons using equal sections and weighting factors. Weighted average of the upper 25 cm was used for the evaluation of soil pH, organic matter, available phosphorus, total nitrogen and sum of basic cations, and apparent CEC in the B horizon at a depth of 50 cm or above a lithic contact was calculated (Sys *et al.*, 1991b, 1993).

The soils were characterized by opening pedons at representative sites on the identified mapping units, while the relevant landscape characteristics were recorded during the pedon site characterization (Table 2). The description of the soil site and pedon were made following the FAO (2006) procedures. The relevant soil properties were determined in the laboratory following standard procedures and analytical methods for each pa-

rometer.

Selection and description of LUTs

The area is dominated by rainfed crop production (agriculture) with low income level subsistence farming. It is generally characterized by low capital community, low market orientation, low technical knowledge of land users, labor intensive, non-recommended use of improved agriculture (e.g. chemical fertilizers), small and fragmented land holding and completely non-mechanized agriculture. According to the information obtained from the *Kebele* agricultural experts, the average size of land holding is 1.25 ha per household and their major sources of traction for ploughing are oxen.

Barley (*Hordeum vulgare* L.) and wheat (*Triticum aestivum* L.) were selected as priority land utilization types (LUTs) for the suitability evaluation of the land against their requirements. This selection was made according to their dominance (area coverage) and importance, but low productivity as per the information obtained from discussion held with the agricultural experts of the *Kebele* and information obtained from farmers.

Suitability evaluation (matching) and production of suitability maps

The maximum limitation method, which takes the most limiting characteristics as defining the land suitability class, was applied for determination of the suitability classes of land characteristics (FAO, 1983; Sys *et al.*, 1991a). Selected parameters were placed in suitability classes (evaluation *sensu stricto*) by matching with the requirements of the selected crops. Arc View and Arc GIS 10 software was used for the production of the suitability maps of the mapping units for the selected LUTs.

RESULTS AND DISCUSSION

Physical Land Suitability Evaluation for Rainfed Agriculture

Start and end of growing, humid period and length of growing period

The study area followed the normal growing period type that corresponds with the FAO working definition which exhibits a humid period (precipitation exceeding potential evapotranspiration) and the start of the growing period was obviously based on the start of the rainy season. The average reference evapotranspiration (ET_0) of the areas was estimated to be 115.8 mm/month (3.8 mm/day). The analysis results of the long term average monthly rainfall and ET_0 data using both graphic and linear interpolation

methods revealed that the growing period in the study area starts on June 17th (second decade of June) and, the rain and rainy season ends on September 19th (second decade of September).

Humid period starts on June 24th (third decade of June) and ends on September 8th (first decade of September). Therefore, the period commencing from the start of growing period extending to end of rains in the study area covers around 95 days according to the computation of the indicated methods. Adding the additional number of days required to evapotranspire the assumed 100 mm of water expected to be stored within the soil at the end of the rains, the growing period extends up to October 15th (second decade of October), which is a total of 121 days. This means that barley and wheat varieties with a maximum crop cycle of 121 days can fit into the growing period of the study area or can be grown using rainfed agriculture. The total rainfall and the mean daily temperature of the growing period were found to be 630.28 mm and 14.05 °C, respectively.

It is usually recommended to start sowing as early as possible in the growing period. FAO (1983) further recommends starting of planting in the first decade that receives 30 mm of rain. Therefore, from the growing period the first decade that receives greater than 30 mm of rainfall is the third decade of June (June 21st to 30th). This indicates that, for Kabe Subwatershed, the planting time starts on June 21st.

Selection of barley and wheat varieties

Differences in days to maturity (maturity group), the culmination of all the development and growth processes throughout the life cycle in which all structures have attained their full size, exist among barley and wheat varieties. FAO (2012) categorized barley into spring varieties with growing cycle of 90 to 130 days and winter varieties with growing cycle that ranges from 180 to 250 days. Furthermore, Sys *et al.* (1993) categorized wheat varieties into spring wheat with length of total growing period (life cycle) that ranges from 100 to 130 days and winter wheat with length of total growing period that ranges from 180 to 250 days. In addition, Oromia Water Works Design and Supervision Enterprise (OWWDSE, 2012) reported that the length of the growing cycle for spring wheat is 100 to 130 days.

The mean daily temperature in the study area during the growing period is less than 20 °C. Since barley and wheat have similar climatic requirements, the optimum mean daily temperature for good performance and production of food barley and wheat is 15 to 20 °C (Appendix Tables 1 and 2). Temperature requirements, expressed as sum of mean daily temperatures, during the growing period in the study area are 1700.11 degree days. Using the lower limit optimum mean daily temperature (15 °C), the 1700.11 degree days are reached after 113 days in the Subwatershed. Therefore, following the above variety

classification and based on the determined length of growing period of the study area, and mean temperature during the growing period, it seems appropriate to choose highland spring barley and wheat varieties with a crop cycle of 113 to 121 days for further suitability evaluation.

Suitability evaluation of soil mapping units

Climatic suitability evaluation for spring barley and wheat (113-121 days) production

The results of the overall climatic suitability evaluation showed that climate of the study area is moderately suitable (S2) for both spring barley and wheat (113 to 121 days crop cycle) varieties production under rainfed conditions (Table 1). The main limiting factor is the lower mean daily temperature condition of the study area relative to the optimum condition which tends to delay maturity. The requirement table in Appendix Tables 1 and 2 indicate that the highly suitable mean daily temperature range for spring barley and wheat varieties is between 15 and 20 °C. However, the mean daily temperature of the study area during the growing cycle is 14.05 °C falling in the range of 12 to 15 °C, which is moderately suitable (S2).

Soil and landscape suitability evaluation for rainfed spring barley and wheat production

The results of the ultimate soil and landscape suitability evaluation showed that soil mapping unit SMU4 is marginally suitable (S3) for rainfed spring barley and wheat production (Table 2). Imperfect to poor soil drainage condition, low total nitrogen, low organic matter content, very hard (dry), firm (moist) and very sticky; plastic to very plastic (wet) soil consistence, and common flood hazard were found to be the limiting factors in the mapping unit. The indicated limitations on soil physical characteristics affect the drainage characteristics of the soils by depriving of oxygen from the root depth during the rainy season. Newman and Newman (2008) stated that barley is very susceptible to water logging and grows and perform best particularly on well to moderately well drained soils in which water and air can move freely but not sandy. Similarly, suitable moist, good fertility status and aerated soil are the main soil factors for the optimum growth and production of wheat (FAO, 2002). However, the mapping unit has imperfect to poorly drained soil that can halt barley and wheat growth and production.

The requirement table in Appendix Table 1 indicates that barley can be grow successfully in soils with OM content greater than 2% and total nitrogen greater than 0.15%, respectively. Similarly, as shown in the requirement table in Appendix Table 2 the highly suitable (S1) limits of total nitrogen and OM content for the production of wheat are > 0.12% and > 2.5%. However, in soil mapping unit SMU4 both are so severe limitations that benefits are

reduced and/or the inputs needed to sustain production are increased so that this cost is only marginally justified (Table 2).

In addition, flooding hazard was also found to be one of the serious limitations for rainfed spring barley and wheat productions due to its damage during the rainy season specially when high rainfall exists. Flood hazard refers to damage by water above the ground surface, which may be caused in two ways: by standing water (inundation) which causes drainage impedence (causes damage to crops by depriving them of oxygen) and moving water that result in flattening or uprooting of a crop or cover it with silt (FAO, 1983). Flood hazard need not only affect the crop, but can refer to damage to the soil and to infrastructure related to the land use.

On the other hand, soil mapping units SMU1, SMU2 and SMU3 for spring barley, and SMU2 and SMU3 for spring wheat production are currently not suitable (with limitations to sustained use that cannot be overcome at a currently acceptable cost) due to problems related to erosion hazard (Table 2). The requirement table in Appendix Tables 1 and 2 indicate that successful growth and production of spring barley and wheat is in areas where the slope range is below 8%. Field investigation of the study area indicated that slope of the mapping units is $\geq 20\%$, which falls in the range of currently unsuitable for the crops. Such hilly topography and convex moderately steep to steep nature of the slope is likely to cause severe soil erosion hazard. In line with this finding, Tadele *et al.* (2013) revealed that soil erosion, which results in deterioration of soil quality including soil fertility, is among the major challenges in the highlands of Ethiopia (Table 2).

The physical suitability evaluation results and assessments using the required and semi-detailed local experience (field investigation), soil and landscape characteristics of the study area showed that soil mapping unit SMU1 found to be the area with relatively more serious and influential limiting factors (constraints) than the previously discussed mapping units for the production of spring wheat (Table 2). The mapping unit is permanently unsuitable (N2) for rainfed spring wheat production due to constraints related to erosion hazard (slope). The erosion hazard assessment obtained by field observations about intensity of phenomena and area affected; the synthetic scheme showed in Appendix Table 2, and identified characteristic is out of range from classes rated as highly suitable and found to be the leading limitation for the production of wheat under rainfed agriculture. In line with this finding, Chilot *et al.* (2002) reported that in the highlands of Ethiopia, particularly the uplands and hillsides of higher altitudes, soils become shallow and stony as a result of severe soil erosion and nutrient depletion. Due to the highly steep and undulating nature of the land in these areas, soil washes down the slope every year and creates impoverished soils that are unsuitable for crop production.

Table 1. Climatic suitability evaluation for spring barley and wheat (113-121 days) production.

Land qualities	Land requirements			Factor rating	
	Diagnostic factor	Unit	Factor value	Barley	Wheat
Temperature regime	Mean temperature in growing period	°C	14.05	S2	S2
Moisture availability	Length of growing period	days	121	S1	S1
	Total rainfall in growing period	mm	630.28	S1	S1
Overall climatic suitability				S2	S2

Table 2. Evaluation of soil mapping units for spring barley and wheat (113-121 days) varieties.

Land requirements			Mapping units											
			SMU1			SMU2			SMU3			SMU4		
Land qualities	Diagnostic factor	Unit	Factor value	Factor rating		Factor value	Factor rating		Factor value	Factor rating		Factor value	Factor rating	
				Barley	Wheat		Barley	Wheat		Barley	Wheat		Barley	Wheat
Oxygen availability	Soil drainage class	Class	MW	S2	S2	W	S1	S1	MW	S2	S2	I-P	S3	S3
Nutrient availability	Soil reaction	pH-H ₂ O	6.24	S1	S2	6.27	S1	S2	6.33	S1	S2	6.22	S1	S2
	Organic matter	%	1.31	S3	S3	1.51	S3	S2	1.45	S3	S3	1.02	S3	S3
	Total nitrogen	%	0.05	S3	S3	0.08	S3	S2	0.09	S3	S2	0.08	S3	S2
	Av. P (Bray I)	mgkg ⁻¹	16.90	S1	S1	37.73	S1	S1	17.65	S1	S1	21.57	S1	S1
Nutrient retention capacity	Apparent CEC	cmol(+) kg ⁻¹ clay	88.39	S1	S1	142.44	S1	S1	68.09	S1	S1	101.8	S1	S1
	Sum of basic cations	cmol(+) kg ⁻¹ soil	20.25	S1	S1	16.33	S1	S1	17.46	S1	S1	25.37	S1	S1
Rooting condition	Effective soil depth	cm	25	S3	S3	100	S1	S2	160	S1	S1	130	S1	S1
Soil workability	texture/ structure	Class	SCL, GR	S2	S2	SL, GR	S3	S3	SCL, GR	S2	S2	C<60, AS	S1	S1
	Dry, moist and wet Consistence	Consistence	SHA, VFR, ST, SPL	S2	S1	SHA, LO, SST, NPL	S1	S1	SHA, VFR, ST, SPL	S2	S1	2-5%	S3	S3
	Coarse fragments	%	15-40	S3	S2	5-15	S1	S1	2-5%	S1	S1	0-3	S1	S1
	Stoniness	%	3-9	S2	S2	3-9	S2	S2	3-9	S2	S2	F2	S1	S1
Flood hazard	Frequency	Class	F0	S1	S1	F0	S1	S1	F0	S1	S1	5.5	S3	S3
Erosion hazard	Slope	%	33	N1	N2	23	N1	N1	20	N1	N1	M-L	S1	S1
	Observed erosion	Class	S-W	N1	N1	S-W	N1	N1	S-W	N1	N1	2-5%	S2	S2
Overall soil and landscape suitability				N1	N2	N1	N1	N1	N1	N1	S3	S3		

Note: MW = moderately well drained, SCL = sandy clay loam, MA = massive, SHA = slightly hard, VFR = very friable, ST = sticky, SPL = slightly plastic, F0 = no risk, S-W = severe-widespread.

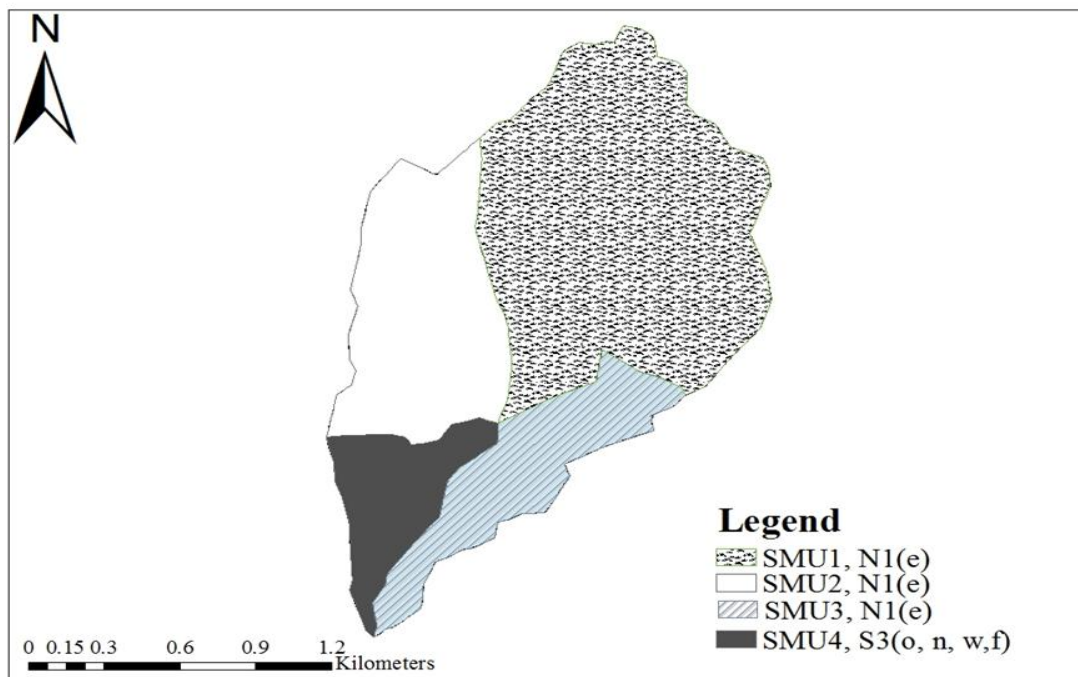


Figure 2. Overall current suitability map of the four soil mapping units for spring barley (113-121 days) production under rainfed agriculture at Kabe Subwatershed.

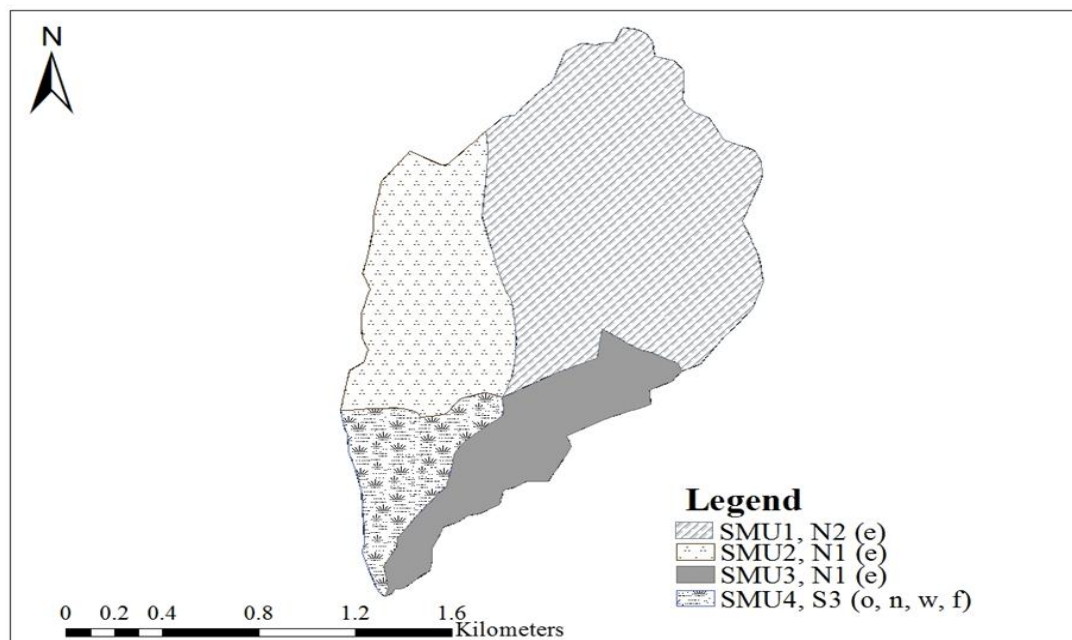


Figure 3. Overall current suitability map of the four soil mapping units for spring wheat (113-121 days) production under rainfed agriculture at Kabe Subwatershed.

The investigated limitation to sustained use cannot be overcome at a currently acceptable cost in the mapping unit (Table 2).

In addition to the above indicated limitations, the other soil and landscape related constraint in soil mapping unit SMU4 to both spring barley and wheat production is

Table 3. Overall suitability evaluation results of the four soil mapping units of Kabe Subwatershed for barley and wheat production using maximum limitation method.

LUT	Soil mapping unit	Climatic suitability	Soil and landscape suitability	Overall suitability	current	Overall potential suitability	Area coverage	
							ha	%
Spring barley (113-121 days)	SMU1	S2 (t)	N1 (e)	N1 (e)		N1 (e)	140.7	51.39
	SMU2	S2 (t)	N1 (e)	N1 (e)		N1 (e)	66.0	24.11
	SMU3	S2 (t)	N1 (e)	N1 (e)		N1 (e)	39.9	14.57
	SMU4	S2 (t)	S3 (o, n, w, f)	S3 (o, n, w, f)		S3 (w)	27.2	9.93
Spring wheat (113-121 days)	SMU1	S2 (t)	N2 (e)	N2 (e)		N2 (e)	140.7	51.39
	SMU2	S2 (t)	N1 (e)	N1 (e)		N1 (e)	66.0	24.11
	SMU3	S2 (t)	N1(e)	N1(e)		N1(e)	39.9	14.57
	SMU4	S2 (t)	S3 (o, n, w, f)	S3 (o, n, w, f)		S3 (w)	27.2	9.93

Note: symbols in parenthesis are major limiting factors; o = oxygen availability, n = nutrient availability (low OM and total N for barley; low OM for wheat), w = soil workability (soil consistence), f = flood hazard (common flooding), e = erosion hazard (slope steepness and observed erosion).

erosion hazard (moderately suitable). Moreover, soil reaction (pH) (moderately suitable) and total nitrogen (moderately suitable) are the other soil and landscape related constraints to spring wheat production in the mapping unit (Table 2). The nutrient availability constraints (low OM, total N and soil pH) can be corrected by minor management (application of fertilizers and liming), and the common flood and poor drainage require moderate land improvement works. However, the soil workability constraint related to consistence cannot be changed by management since it is permanent limitation. Therefore the soil mapping unit will remain potentially marginally suitable (S3) for spring barley and wheat production.

Drainage and soil texture (moderately suitable) in soil mapping units SMU1 and SMU3, and stoniness (moderately suitable) in soil mapping units SMU1, SMU2 and SMU3, are the other soil and landscape related constraints for both rainfed spring barley and wheat production. Soil consistence in mapping units SMU1 and SMU3 was moderately suitable for spring barley production. Similarly, soil pH in mapping units SMU1, SMU2 and SMU3, total nitrogen in mapping units SMU2 and SMU3, coarse fragments in mapping unit SMU1, organic matter and soil depth in mapping unit SMU2 were moderately suitable (S2) for spring wheat production.

On the other hand, organic matter in mapping units SMU1 and SMU3, total nitrogen and soil depth in mapping unit SMU1 and soil texture in mapping unit SMU2 were marginally suitable for both rainfed spring barley and wheat production (Table 2). In addition, coarse fragments in mapping unit SMU1 and total nitrogen in mapping units SMU2 and SMU3 were marginally suitable for spring barley production. Even if most of the indicated limitations in mapping units SMU1, SMU2 and SMU3 can be modified by management, the slope steepness cannot be reduced and corrected by management. Therefore, mapping units SMU1, SMU2 and SMU3 remain currently unsuitable (N1) for spring

barley production. Similarly, soil mapping unit SMU1 remain permanently unsuitable (N2) and mapping units SMU2 and SMU3 remain currently unsuitable (N1) for spring wheat production. But, the use of different soil and water conservation practices can increase the productivity of the mapping units by reducing erosion and maintaining or restore the capacity of the soil to retain water along with nutrients.

Overall suitability evaluation

The ultimate overall suitability results were obtained by combining climatic and, soil and landscape suitability classes for both crops as shown in Table 3. Since the study area fall under the same climatic condition the climatic characteristics are the same for all mapping units. Consequently, the climatic suitability for all the mapping units is set the same. The results of the overall suitability evaluation of the four mapping units showed that soil mapping unit SMU4, which covers 27.2 ha (9.93%) of the study area, is marginally suitable (S3), while SMU2 and SMU3, each covering 66.0 ha (24.11%) and 39.9 ha (14.57%) of the Subwatershed, are currently unsuitable (N1) for spring barley and wheat production under subsistence rainfed agriculture (Table 3 and, Figures 2 and 3). On the other hand, soil mapping unit SMU1, which covers 140.7 ha (51.39%) of the study area is permanently unsuitable (N2) for spring wheat production but currently unsuitable (N1) for barley production under subsistence rainfed agriculture (Table 2). In relation to the present finding, IIASA/FAO (2002) reported that on the basis of available soil, terrain and climatic data from 639.5 (10⁶ ha) of land of east Africa, about 404 (10⁶ ha) of land suffer from sever constraints related to too dry (18.5%), too steep (10.2%) and poor soil (53.5%) conditions for rainfed crop production.

For the production of spring barley soil drainage class, OM content, total nitrogen, soil consistence and flooding hazard were found to be the limiting factors in soil mapp-

ing unit SMU4. Similarly, the production of spring barley found to be limited by erosion hazard in all the rest mapping units as presented in Table 3. On the other hand, for the production of spring wheat soil drainage class, OM content, soil consistence and flooding hazard were found to be the limiting factors in soil mapping unit SMU4. Besides, erosion hazard in soil mapping units SMU1, SMU2 and SMU3 found to be the main constraint for the production of spring wheat.

Even though, correctable limiting factors are present, all the mapping units remained the same due to permanent limitations related to consistence in soil mapping unit SMU4 and slope steepness in the remaining mapping units (Table 3). However, if all the correctable limiting constraints are modified through ordinary management or major land improvement and soil and water conservation practices are implemented, the mapping units can increase productivity. Implementation of appropriate land use practices that can fit to the present potential of the area, like plantation can be one of the development options.

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Appendix Table 1. Crop environmental requirements for barley (113-121 days) under subsistence rainfed agriculture at the Kabe Subwatershed.

Land use requirements			Factor rating				
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N1	N2
Temperature regime	Mean temperature in growing period	°C	15-20	20-30 12-15	30-40 10-12	-	<10 >40
Moisture availability	Length of growing period	days	110-140	110-90 140-190	90-70 190-230	-	-
	Total rainfall during growing period	mm	300-1100	300-200 1100-1300	200-150 1300-1500	-	<150 >1500
Oxygen availability	Soil drainage class	Class	W	MW	I-P	P	VP,E
Nutrient availability	Soil reaction	pH-H ₂ O	6.2-8.0	<6.2-5.8 >8.0-8.2	<5.8-5.5 >8.2-8.5	<5.5 -	- >8.5
	Organic matter	%	>2	2-1.55	<1.55-0.5	<0.5	-
	Total nitrogen	%	>0.15	0.15-0.10	<0.10-0.04	<0.04	-
	Available P (Bray I)	mgkg ⁻¹	>13	13-6	<6-3	<3	-
Nutrient retention capacity	Apparent CEC	cmol(+) kg ⁻¹ clay	>16	16-8	<8	-	-
	Sum of basic cations	cmol(+) kg ⁻¹ soil	>5	5-3.5	3.5-2	<2	-
Rooting condition	Effective soil depth	cm	>75	75-50	<50-25	-	<10
Soil workability	Soil texture/structure	Class	C<60v, C<60s, SiCL, CL, Si	SC, SCL, C>60v	SL, LS	-	Cm, SiCm, S
	Dry, moist and wet Consistence	Consistence	SO,LO, FR,VFR NST-SST	SHA, HA, ST	VHA, FI-VFI	-	EFI, VP, EHA
	Coarse fragments	%	0-15	15-35	35-55	-	>55
	Stoniness	%	0-3	>3-9	>9-20	-	>20
Flood hazard	Frequency	Class	Fo	F1	F2	F3	F4
Erosion hazard	Slope	%	0-6	>6-10	>10-18	>18-35	>35
	Field observation	Class	N, SI-N, SI-L	M-L, SI-W	S-L, M-W	S-W	ES -W

Note: W = well drained, MW = moderately well drained, I-P = imperfect to poorly drained, P = poorly drained, VP = very poorly drained, E = excessively drained, C<60v = clay less than 60% vertisol structure, C<60s = clay less than 60% blocky structure, SiCL=silty clay loam, CL = clay loam, Si = silt, SC = sandy clay, SCL = sandy clay loam, C>60v = clay greater than 60% vertisol structure, SL = sandy loam, LS = loamy sand, Cm = massive clay, SiCm = massive silty clay, S = sand, SO = soft, LO = loose, FR = friable, VFR = very friable, NST = non sticky, SST = slightly sticky, SHA = slightly hard, HA = hard, ST = sticky, VHA = very hard, FI = firm, VFI = very firm, EFI = extremely firm, VP = very plastic, EHA = extremely hard, Fo = no risk, F1 = slight, F2 = common, F3 = frequent, F4 = permanent, N = Nil, SI-N = Slight-Negligible, SI-L = Slight-Localized, M-L = Moderate-Localized, SI-W = Slight-Widespread, S-L = Sever-Localized, M-W = Moderate-Widespread, S-W = Sever-Widespread, ES-W = Extremely severe-Widespread

Source: Compiled from, Dent and Young, 1981; FAO, 1983; FAO/UNDP, 1984ab; Henok, 2010; IIASA/FAO, 2002; IIASA/FAO, 2012; Jones (2003); Kassa and Mulu, 2012; Newman and Newman (2008); Sanchez *et al.*, 2003; Sys and Riquier, 1980; Sys *et al.*, 1991ab; Sys *et al.*, 1993; Van Diepen *et al.*, 1991

Appendix Table 2. Crop environmental requirements for wheat (113-121 days) under subsistence rainfed agriculture at the Kabe Subwatershed.

Land Requirements			Factor rating				
Land qualities	Diagnostic factor	Unit	S1	S2	S3	N1	N2
Temperature regime	Mean temperature in growing season	°C	15-20	<15-12.5 >20-25	<12.5-8 >25-30	-	<8 >30
Moisture availability	Length of growing period	days	115-150	100-115 150-180	85-100 180-230	-	-
	Total rainfall during growing period	mm	350-1250	<350-250 >1250-1500	<250-200 >1500-1750	-	<200 >1750
Oxygen availability	Soil drainage class	Class	W	MW	I	P	VP,E
Nutrient availability	Soil reaction	pH-H ₂ O	6.5-7.5	<6.5-5.6 >7.5-8.2	<5.6-5.2 >8.2-8.5	<5.2 -	- >8.5
	Organic matter	%	>2.5	2.5-1.5	<1.5-0.5	<0.5	-
	Total nitrogen	%	>0.12	0.12-0.08	<0.08-0.04	<0.04	-
	Available P (Bray I)	mgkg ⁻¹	>10	10-5	<5-3	<3	-
Nutrient retention capacity	Apparent CEC	cmol(+) kg ⁻¹ clay	>16	16-8	<8	-	-
	Sum of basic cations	cmol(+) kg ⁻¹ soil	>5	5-3.5	3.5-2	<2	-
Rooting condition	Effective soil depth	cm	>100	100-50	<50-20	-	<10
Soil workability	Soil texture/ structure	Class	Si, SiCL, C<60s, L, CL	SC, SCL, C>60v, Gr, fB, Cr	LS, SL	-	Cm, SiCm, LcS, fS, cS, S
	Dry, moist and wet Consistence	Consistence	SO, LO, FR, VFR, NST-SST	SHA, HA, FI	VHA, VFI, ST	-	EFI, VP, EHA, VST
	Coarse fragments	%	0-15	>15-35	>35-55	-	>55
	Stoniness	%	0-3	>3-9	>9-20	-	>20
Flood hazard	Frequency	Class	Fo	F1	F2	F3	F4
Erosion hazard	Slope	%	0-6	>6-10	>10-<20	20-30	>30
	Field observation	Class	N, SI-N, SI-L	M-L, SI-W	S-L, M-W	S-W	ES -W

Note: W = well drained, MW = moderately well drained, I = imperfectly drained, P = poorly drained, VP = very poorly drained, E = excessively drained, C<60s = clay less than 60% blocky structure, SiCL=silty clay loam, CL = clay loam, Si = silt, L = loam, SC = sandy clay, SCL = sandy clay loam, C>60v = clay greater than 60% vertisol structure, Gr = granular, SL = sandy loam, LS = loamy sand, P = platy structure, Cm = massive clay, SiCm = massive silty clay, LcS = loamy coarse sand, cS = coarse sand, S = sand, GR = gravelly, SO = soft, LO = loose, FR = friable, VFR = very friable, NST = non sticky, SST = slightly sticky, SHA = slightly hard, HA = hard, ST = sticky, VHA = very hard, FI = firm, VFI = very firm, EFI = extremely firm, VP = very plastic, EHA = extremely hard, VST = very sticky, Fo = no risk, F1 = slight, F2 = common, F3 = frequent, F4 = permanent, N = Nil, SI-N = Slight-Negligible, SI-L = Slight-Localized, M-L = Moderate-Localized, SI-W = Slight-Widespread, S-L = Sever-Localized, M-W = Moderate-Widespread, S-W = Sever-Widespread, ES-W = Extremely severe-Widespread.

Source: Compiled from, Dent and Young, 1981; FAO, 1983; FAO/UNDP, 1984ab; Henok, 2010; FAO, 2002; IIASA/FAO, 2002; IIASA/FAO, 2012; Jones (2003); Kassa and Mulu, 2012; Sanchez *et al.*, 2003; Sys and Riquier, 1980; Sys *et al.*, 1991ab; Sys *et al.*, 1993; Van Diepen *et al.*, 1991; OWWDSE, 2012.