

Integrated Multi-criteria Land Suitability Evaluation and Mapping for Scaling Malt Barley Varieties in Rain-Fed Production Areas of Ethiopia

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Abstract

Information on variety specific land suitability analysis was not available in Ethiopia. Therefore, integrated multi-criteria land suitability analysis and mapping for contrasting malt barley varieties was carried out to identify where and how much potentially suitable land exists in the country. The main factors considered for analysis include rainfall and temperature during the growing period, length of growing period, digital elevation models, (altitude and slope data) and soil characteristics (types, pH, depth, texture and drainage). The malt barley varieties included are late maturing Bekoji-1, EH1847 and Holker; and early maturing Grace, IBON 174/03 and Sabini. For classification of the data layers according to the degree of suitability for each variety, various reports and other relevant information were reviewed and used in defining the limits of the suitability ranges of malt barley varieties. The overall suitability was computed by multiplying the selected criteria weight by the assigned sub-criteria score and summing these values in the ArcGIS Model Builder. The analysis showing the extent and patterns of suitable land area available for the selected malt barley varieties are presented in the form of tabular data and maps. Highly suitable areas for these varieties include: 125,332 ha for Bekoji-1; 124,004 ha for EH1847; 775,312 ha for Grace; 125,356 ha for Holker; 1,677,388 ha for IBON 174/03; and 307,952 ha for Sabini. The results suggest that current improved malt barley varieties can be targeted for scaling out in the identified land suitability classes in the highlands of Ethiopia. Results also suggest that future research and development works should give priority for developing early maturing, acidic and waterlogging soil tolerant malt barley varieties. The results can be useful for policy and decision making to ensure land resources are used in the most productive and sustainable ways and solve the mismatches between current land use and land suitability for malt barley varieties in the country.

Keywords: environmental requirement, Ethiopian highlands, land suitability, malt barley, mapping

1. Introduction

Barley has been an important food and industrial crop in Ethiopia. Although Ethiopia is the second largest barley producer in Africa, accounting for about 25% of the total barley production (Food and Agriculture Organization [FAO], 2014), it has not yet been able to expand malt barley production. The share of malting barley production is quite low and constitutes about 10-15% of the total barley area of about 959,273 ha in 2016/2017 *meher* season (Ethiopian Institute of Agricultural Research [EIAR], 2015; Central Statistical Agency [CSA], 2017). On the other hand, the booming demand of breweries for supply of quality malt barley has been increasing in Ethiopia (Gessesse, 2017). However, due to low productivity, poor malt quality, and very limited expansion of malt barley production, the net import bill for malt barley jumped from US\$240 thousand in 1997 to US\$40 million in 2014 and is projected to reach as high as US\$420 million by 2025 (Lakew, Yigezu, Yirga, & Aw-Hassan, 2015; Rashid, Abate, Lemma, Warner, Kasa, & Minot, 2015).

Abiotic and biotic stresses, weak technology generation and transfer, limited availability and access to inputs, sub-optimal application of fertilizers, and poor access to markets due to poor linkages between the farmer producers and the brewing industry are the main constraints responsible for low productivity, poor malt quality and limited expansion of malt barley production in Ethiopia. Among abiotic stresses, it is a well-established fact that the physical environment strongly affects the genetic potential and quality of malt barley (Ajith, 2009; Muhe, 2011; EIAR, 2015; Mehari, Alamerew, & Lakew, 2015; Mekonnen, 2013; Rashid, Abate, Lemma, Warner, Kasa, & Minot, 2015). In our study, the physical environment includes the soil type, soil depth, soil pH, soil texture, soil drainage, land slope, altitude, length of growing period, and climate (rainfall and temperature). The interaction and/or main effects of these components of the physical environment not only determine productivity but also the very existence and distribution of plant species in Ethiopia (Boke & Fekadu, 2019; Gashaw, Tulu, & Argaw, 2017; Hurni, 1998; Merga & Ahmed, 2019; MoA, 1998). Different reports showed the large contrasts in elevation and topography that characterize the country are very effective in controlling local climate conditions to such an extent that even sites within a short distance may show very different climatic conditions (Fazzini, Bisci, & Billi, 2015; FAO, 2016; Jembere, Mamo, & Kibret, 2017). The large elevation and topographic variability results in a wide range of temperatures that may be as low as -7°C in the Bale Mountains (4,377 m above sea level) and as high as 50°C in the Danakil Depression of 115-125 m below sea level. Similarly, the long-term observations indicate that higher rainfalls are recorded in the western highlands, with 2,101 mm year⁻¹ at Gore, and ≤ 145 mm year⁻¹ in the desert areas of Danakil Depression in Afar region.

Cognizant of this fact, one of the major objectives of the national malt barley improvement program has been to develop resilient malt barley varieties for production under such variable environmental conditions in the highlands of Ethiopia. Since its inception some 50 years ago, the Ethiopian national agricultural research system has released ten malt barley varieties with different yield potentials, malt qualities, adaptation areas and stability (Ministry of Agriculture [MoA], 2010). However, national malt barley productivity was not competitive enough for smallholder farmers to expand production due to weak technology transfer capacity (Rashid et al., 2015) and lack of well-structured land suitability information. In Ethiopia where smallholder farmers account 95% of agricultural production and 85% of all employment, 40% of the farming households operate on less than 0.5 ha, 64% on less than 1 ha, and 87% on less than 2 ha (FAO, 2011 citing Gebreselassie, 2007) although under rainfed agriculture an average family of 6 persons requires around 2.5 to 2.8 ha land to meet annual household requirements. This calls for agricultural intensification, where in our capacity, at least start with land suitability classification of malt barley varieties to improve productivity up to the potential of available natural resources and maintain the grain quality under the recommended management technologies.

The process of land suitability classification is the appraisal and grouping of specific areas of land in terms of their suitability for defined uses (FAO, 1976). Land suitability classification for agriculture is very important for future planning to help decision-makers and agricultural development planners determine how appropriate use of the land in a location is more suitable for certain agricultural use (Singha & Swain, 2016). Geographic Information Systems (GIS) based land suitability analysis enables a large amount of different geospatial and associated information to be assembled, combined, overlaid, modeled and mapped. GIS has contributed to the speed and efficiency of the overall planning process in agricultural land use suitability since it enables quick and efficient access to large amounts of information, exhibiting relationships, patterns, and trends that are useful in monitoring land use potential and suitability evaluation. It is also useful tool for scaling proven technologies and packages of practices including the specific crops and crop varieties to address the yield and nutritional gaps (Singha & Swain, 2016; Löw, Biradar, Dubovyk, Fliemann, Akramkhanov, Vallejo, & Waldner, 2018).

Records show that GIS based land suitability evaluations for rainfed and irrigated agriculture in Ethiopia have been going on since 1989 (Radcliffe & Bechtold, 1989; Rabia, 2012; Girma, Getahun, & Babu, 2019). This process recently evolved to multi-criteria crop level land suitability analysis and mapping (Yitbarek, Kibret, Gebrekidan, & Beyene, 2013; Selassie, Ayalew, Elias, & Getahun, 2014; Yohannes & Soromessa, 2018). The crop level suitability analysis results for malt barley indicated that there is 1,897,256 ha of land which is highly suitable for malt barley production in Ethiopia (Nigussie, Tibebe, & Demelash, 2018). However, crop level land suitability analysis does not consider variety by environment interactions and therefore does not indicate which variety fits best to which environmental conditions. It is, therefore, very important to map the agricultural land with its orographic and agroclimatic information to show the extent and distribution of land areas that are potentially suitable for contrasting malt barley varieties to enhance productivity and scaling in Ethiopia. Our integrated multi-criteria land suitability evaluation and mapping focused on physical environments such as soil type, soil depth, soil pH, soil texture, soil drainage, land slope, altitude, length of growing period, rainfall, and temperature requirements of each test malt barley variety.

2. Materials and Methods

2.1 Study Area

The study area, Ethiopia, is in geographic coordinates between 3°30' and 14°50'N latitude, and 32°42' and 48°12'E longitude with total surface area of 1,104,300 km² of which about 1,000,000 km² is land area (Kassie, 2014). It is a large and ecologically diverse country having nine regional states (Afar; Amhara; Benishangul-Gumuz [BSG]; Gambela; Harari; Oromia; Somali; Southern Nations, Nationalities and Peoples [SNNP]; Tigray) and two chartered cities (Addis Ababa and Dire Dawa). Each regional state is subdivided into administrative zones, districts and then to *kebeles* (the smallest administrative units). Our study excluded water bodies and land area of the two chartered cities and Harari Regional State.

Rainfall and temperature patterns vary widely because of Ethiopia's location in the tropics and its diverse topography. Moreover, the diversity of the country's terrain determines regional variations in climate, natural vegetation, and soil composition (Fazzini, Bisci, & Billi, 2015; FAO, 2016; Jembere, Mamo, & Kibret, 2017). Topographically, it consists of a central high plateau bisected by the Great Rift Valley into northern and southern highlands and surrounded by lowlands. The plateau varies from 1,500 to 3,000 meters above sea level and features mountainous uplands reaching the peak at Ras Dejen with the elevation of 4550 m above sea level (with the usual violent snow falls at night which melts when the temperature reaches 5-8 °C at midday), separated by deep gorges and river valleys. The lowlands lower than 1500 m above sea level ends with Danakil Depression in the east which is 115-125 meters below sea level and is one of the hottest (as high as 50 °C) places on earth.

2.2 Crop Varieties

Depending on data availability, varietal choices for malt barley were made based on the current production and altitude wise area coverage and recommendation in the technology transfer; productivity; earliness; plant height and straw yield to meet feed requirement for livestock; and grain protein content and seed boldness for malt quality. The malt barley varieties included in this analysis work are listed in Table 1.

Table 1. Selected characteristics of malt barley varieties used for land suitability mapping

Variety	Year of release	Days to flowering after emergence*	Grain yield with recommended management (t ha ⁻¹)	Grain protein content (%)	Thousand grain weight (g)	Plant height at heading* (cm)	Recommended altitude (masl)
Bekoji-1	2010	77	3.5-5.0	11.7	46.6	108.8	2,300-2,800
EH1847	2011	80	3.5-4.4	11.2	46.0	101.2	2,200-2,800
Grace	2013	Na	2.0-4.0	10.5	42.0	na	2,000-2,400
Holker	1979	80	2.4-3.1	10.4	41.1	104.0	2,500-3,000
IBON174/03	2012	67	3.0-5.7	10.0	46.5	88.2	2,000-2,800
Sabini	2011	72	2.5-4.9	8.5	45.0	87.6	2,300-2,500

Note. na = no data available for it was not tested at DBARC.

Source: National Seed Industry Agency (NSIA), 1998; Ministry of Agriculture (MoA), 2010-212; Ministry of Agriculture and Rural Development (MoARD), 2013; and unpublished Regional Variety Trial data submitted to MoA; *unpublished data of Debre Birhan Agricultural Research Center (DBARC) at 2,810 masl.

2.3 Geospatial Data

To carry out a land suitability evaluation, spatial data layers were prepared. The main factors affecting plant growth parameters were included in the analysis: climate layers, topography (digital elevation models, *i.e.*, altitude and slope data), soil types and soil properties [chemical (pH) and physical (depth, texture, and drainage)]. Administrative boundaries and infrastructure (roads, towns, and other facilities) were also used to prepare the final map and generate the tabular data.

Greater emphasis was given to altitude as it largely influences climate which plays a major role in crop production (Hurni, 1998). The climate data used were rainfall and temperature surface maps (during the growing period) interpolated at a resolution of about 300 m which again resampled to 200 m to match the 200 m analysis resolution; and length of growing period with a slight modification (*i.e.*, joining the values of dependable length of period and converting to raster (pixel based)). Source of these data was Woody Biomass Inventory and Strategic Planning Project (WBISPP, 2004) of the Ethiopian Ministry of Agriculture. Climatic conditions can vary widely from year to year, and this was addressed by using long-term average of rainfall and temperature;

this approach is valid if the aim is to assess overall suitability or potential and not to model crop growth in any one year (Pettapiece, 1995).

The soil properties were extracted from the Soil and Terrain Database of East Africa and gridded soil database of 250 mm (International Soil Reference Information Center [ISRIC], 2015), while the soil type used was from WBISPP (2004). For the altitude information, the Shuttle Radar Topography Mission (SRTM) 90 m digital elevation model (DEM) database (Jarvis, Reuter, Nelson and Guevara, 2008) was used and the same DEM used for topographic analysis such as generating slope maps. These data were resampled to a common spatial resolution of 200 m for the spatial analysis in the GIS domain.

2.4 Defining the Limits of Environmental Requirements for Malt Barley Varieties

To define the suitability classes according to the land use types, several literatures (*e.g.*, NSIA, 1998; MoA, 2010-2012; MoARD, 2013; unpublished research reports in the national agricultural research system) and qualified researchers were consulted. The land evaluations study conducted by FAO (1984), and by Sys, Ranst, Debaveye, and Bernaert (1993) were used as a general guide to derive thresholds for defining the suitability categories.

For classification of the data layers according to the degree of suitability for each variety specific to environmental conditions, the existing digital and analogue maps, reports, and other relevant information were reviewed and used in defining the limits of the suitability ranges of each malt barley variety. The environmental requirements of the target varieties were defined by means of a set of critical values, which determine the limits between the land suitability classes. The suitability classes, reflecting the degree of suitability, were set as S₁ (highly suitable), S₂ (moderately suitable), and S₃ (marginally suitable) and N (not suitable) based on the assumptions indicated in the FAO land suitability classification structure presented in Table 2. According to FAO classification, S₁ corresponds to 85-100%, S₂ to 60-85%, S₃ to 40-60%, N₁ to 25-40% and N₂ to 25-0% (Elsheikh & Abdalla, 2016) of optimum yield under the recommended management practices.

Table 2. Structure of the FAO land suitability classification

Code	Class name	Description
S ₁	Highly suitable	Land having no significant limitations to sustained application of a given use, or only minor limitations that will not significantly reduce productivity and will not raise inputs above an acceptable level.
S ₂	Moderately suitable	Land having limitations which, in aggregate, are moderately severe for sustained application of a given use; the limitations will reduce productivity and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciably low to that expected on S ₁ land.
S ₃	Marginally suitable	Land having limitations which, in aggregate, are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.
N	Not suitable	Land that cannot support the land use on a sustained basis, or land on which benefits do not justify necessary inputs

Source. FAO, 1976, 1993.

Since the analysis is raster (pixel) based, some of the data, which were in vector format (object based), were converted to uniform raster datasets. The important GIS layers of environmental factors affecting the growth of malt barley varieties were identified and each layer's pixel values were classified and assigned weight. Following this, the environmental factor layers were compared among themselves and ranked. Based on the rate and rank assigned to each pixel, the land suitability map for each variety was computed. The classification of each layer into suitability categories was done using Reclass by Table function in ArcGIS spatial analyst (ESRI GIS package) tool. The reclassification is implemented in the model by preparing separate tables for each factor/criteria layer and malt barley variety. The environmental requirements of the target varieties were defined by means of a set of critical values, which determine the limits between the land suitability classes. Because of space limitations, it is difficult to show all details of defined critical values of each variety's environmental requirements, thus, some selected examples by grouping the varieties into late versus early are presented in Table 3. Early malt barley varieties are Grace, IBON 174/03 and Sabini while late maturing ones are Bekoji-1, EH1847 and Holker.

Table 3. Environmental information used in land suitability mapping of early versus late maturing malt barley varieties

Maturity group of varieties	Environmental parameters	Critical values/ratings in each suitability class			
		S ₁	S ₂	S ₃	N
Early	Altitude (masl)	2000-3000	1800-2000; 3000-3200	1500-1800; 3200-3500	<1500; >3500
Late		2600-3000	2400-2600; 3000-3100	2000-2400; 3100-3200	<2000; >3200
Early	Rainfall (mm)	900-1400	700-900; 1400-1600	500-700; 1600-1800	<500; >1800
Late		900-1400	800-900; 1400-1500	600-800; 1500-1600	<600; >1600
Early	Temperature (°C)	12-17	10-12; 17-19	8-10; 19-21	<8; >21
Late		11-13	10-11; 13-15	9-10; 15-17	<9; >17
Early	LGP (days)	110-180	100-110; 180-190	90-100; 190-200	<90; >200
Late		150-180	140-150; 180-190	120-140; 190-200	<120; >200
Early	Soil type	Nitisols, Cambisols, Luvisols, Phaeozems	Fluvisols, Andosols, Gleysols, Histosols, Chernozems	Vertisols, Acrisols, Rendzinas	Lithosols, Regosols, Xarosols, Solonchaks, Yermosols
Late					
Early	Texture class	Loam, Silt-loam, Sandy clay-loam	Clay-loam, Silty clay-loam	Sandy-loam, Sandy-clay, Silt, Silty-clay, Clay	Sand, Loamy sand
Late					
Early	Drainage class	Well drained	Somewhat excessively drained, Moderately well drained	Excessively drained, Imperfectly drained	Poor
Late					
Early	Soil pH	6.0-7.5	5.0-6.0; 7.5-8.0	4.5-5.0; 8.0-8.5	<4.5; >8.5
Late					
Early	Soil depth (cm)	>80	60-80	40-60	<40
Late					
Early	Slope (%)	2-15	15-25	1-2; 25-30	<1; >30
Late					

Note. masl = meters above sea level; LGP = length of growing period mainly affected by altitude (through influencing climatic variables) and water holding capacity of soil.

2.5 Calculation of Weight for Criteria Layers and Overall Suitability Analysis

The overall suitability map is the combined result of the altitude, slope, soil types and soil properties, and the climate layers. The weighted overlay approach built on ArcGIS ModelBuilder was used for the overlay analysis to solve such multi-criteria problems of suitability. The suitability criteria layers were assigned weights to account for their relative importance and overlaid using the weighted overlay tool to produce the overall land suitability map. The purpose of weighting is to express the relative importance of each factor regarding the effects on crop yield and growth rate (Perveen, Nagasawa, Uddin, & Delowar, 2007).

The analytic hierarchy process (AHP) developed by Saaty (1987) was used to calculate the weights for the different criteria. AHP relies on pairwise comparisons that assign values based on relative importance of criteria layers. The criteria were evaluated, and numerical scales of measurement were derived through comparing against the goal for importance. The pairwise comparison scales were assigned through discussion among experts. The overall suitability is computed by multiplying the selected criteria weight (W_i) by the assigned sub-criteria score (X_i) and summing these values in the ArcGIS Model Builder (see Equation 1):

$$S = \sum_{i=1}^n W_i \cdot X_i \quad (1)$$

where, S denotes the final land suitability score, W_i denotes the weight of the corresponding suitability criteria, X_i denotes the assigned sub-criteria score of i suitability criteria and n is the total number of criteria maps.

The final suitability result (maps and tabular data) including the explanatory document are prepared both in softcopy and hardcopy. The eventual relative weight values of these multi-criteria are 16.90, 14.40, 12.54, 9.75, 9.75, 9.44, 8.70, 7.71, 5.65 and 5.16% for altitude, rainfall, temperature, soil type, texture, length of growing period, drainage, soil pH, soil depth and slope, respectively. The flow diagram shows the steps followed for suitability analysis (Figure 1):

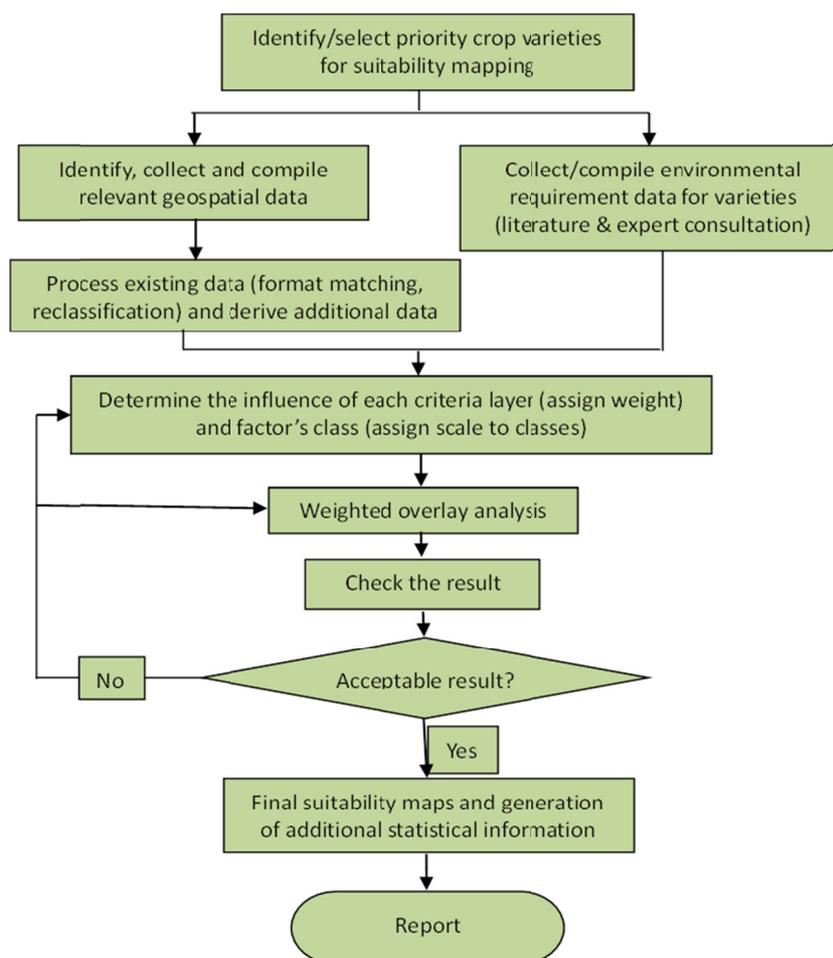


Figure 1. Flowchart of steps for suitability analysis

3. Results

In addition to the presentation of the result for each variety in the subsequent sub-sections, major administrative zones with relatively larger proportion of highly suitable (S_1) and moderately suitable (S_2) land areas among target administrative zones in regional states of Ethiopia are presented in Table 4 for better understanding and comparison of differences among malt barley varieties. For each variety, 15 administrative zones are listed in decreasing order of land area for S_1 and S_2 across the regional states.

Table 4. Malt barley varieties and administrative zones with relatively larger land area for S₁ and S₂ in Ethiopia

Variety	Suitability classes	Land area (ha)	Major administrative zones
Bekoji-1	S ₁	125,332	West Shewa, South Wollo, North Shewa of Amhara Region, North Gonder, South Gonder, Guji, South West Shewa, Horo Guduru, East Shewa, Arsi, West Gojam, East Gojam, North Shewa of Oromia Region, West Arsi, Borena
	S ₂	4,342,044	Jimma, Arsi, Ilubabor, West Shewa, Bale, West Arsi, East Gojam, North Shewa of Oromia Region, West Gojam, South Wollo, Keffa, South Gonder, Guji, East Wellega, North Shewa of Amhara Region
EH 1847	S ₁	124,004	West Shewa, North Shewa of Amhara Region, South West Shewa, South Gonder, Gamo Gofa, Gurage, East Gojam, North Shewa of Oromia Region, Selti, Jimma, North Gonder, South Wollo, Hadiya, South Omo, Dawro
	S ₂	4,330,932	Arsi, West Arsi, West Shewa, North Shewa of Oromia Region, North Shewa of Amhara Region, South Wollo, Jimma, Bale, Gurage, Gamo Gofa, East Gojam, Keffa, Sidama, South West Shewa, Guji
Grace	S ₁	775,312	West Shewa, South Wollo, North Shewa of Amhara Region, North Gonder, South Gonder, Guji, South West Shewa, Horo Guduru, East Shewa, Arsi, West Gojam, East Gojam, North Shewa of Oromia Region, West Arsi, Borena
	S ₂	20,648,764	Jimma, Arsi, Ilubabor, West Shewa, Bale, West Arsi, East Gojam, North Shewa of Oromia Region, West Gojam, South Wollo, Keffa, South Gonder, Guji, East Wellega, North Shewa of Amhara Region
Holker	S ₁	125,356	West Shewa, South West Shewa, North Shewa of Amhara Region, South Gonder, Gamo Gofa, Gurage, Jimma, East Gojam, Selti, North Shewa of Oromia Region, North Gonder, South Wollo, Hadiya, South Omo, Dawro
	S ₂	4,342,756	Arsi, West Arsi, West Shewa, North Shewa of Oromia Region, North Shewa of Amhara Region, South Wollo, Jimma, Bale, Gurage, Gamo Gofa, East Gojam, Keffa, Sidama, South West Shewa, Guji
IBON 174/03	S ₁	1,677,388	West Shewa, North Shewa of Amhara Region, South Gonder, South Wollo, East Gojam, North Shewa of Oromia Region, West Gojam, North Gonder, South West Shewa, East Harerge, Jimma, Horo Guduru, Arsi, Guji, Gurage
	S ₂	11,588,156	Arsi, Jimma, West Arsi, North Shewa of Oromia Region, South Wollo, East Gojam, North Shewa of Amhara Region, West Shewa, Keffa, Bale, Guji, Sidama, South West Shewa, Ilubabor, North Wollo
Sabini	S ₁	307,952	West Shewa, South West Shewa, South Gonder, North Gonder, South Wollo, East Harerge, Arsi, North Shewa of Amhara Region, West Gojam, Guji, East Gojam, North Shewa of Oromia Region, Gedio, Bale, West Harerge
	S ₂	16,358,348	Jimma, Arsi, West Shewa, West Arsi, East Gojam, North Shewa of Oromia Region, South Wollo, North Shewa of Amhara Region, Ilubabor, Keffa, South Gonder, Guji, South West Shewa, Bale, Sidama

Note. An administrative zone may have highly suitable and/or moderately suitable areas as it covers large and diverse geographic area.

The results of the land suitability analysis for each variety are presented in the subsequent sub-sections to show the extent and patterns of land area available for production and scaling up of target malt barley varieties in Ethiopia.

3.1 Variety Bekoji-1 (EH1293/F2-18B-11-1-14-18)

Land suitability analysis and mapping results for variety Bekoji-1 are shown in Table 5 and Figure 2. As indicated in Table 1, variety Bekoji-1 is a relatively high yielding and late-maturing variety which performs best in frost free long growing period in high altitude highlands. Highly suitable areas where it is expected to express its higher potential is very limited, 125,332 ha, as compared to other relatively early maturing varieties like IBON 174/03 (Table 4).

Table 5. Land area and suitability classes for malt barley variety Bekoji-1 production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not Suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	35,240	0.23	860,992	5.53	3,892	0.03	14,663,245	94.22
Oromia	75,392	0.23	2,513,736	7.75	128,084	0.39	29,732,201	91.63
SNNP	14,700	0.13	961,160	8.51	31,268	0.28	10,282,858	91.08
Tigray	0	0	3,400	0.07	0	0	5,017,258	99.93
Afar	0	0	0	0	0	0	9,562,336	100
BSG	0	0	2,668	0.05	0	0	4,997,689	99.95
Gambella	0	0	88	0	0	0	2,570,048	100
Somali	0	0	0	0	0	0	31,561,965	100
Total	125,332	0.11	4,342,044	3.84	163,244	0.14	108,387,600	95.90

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

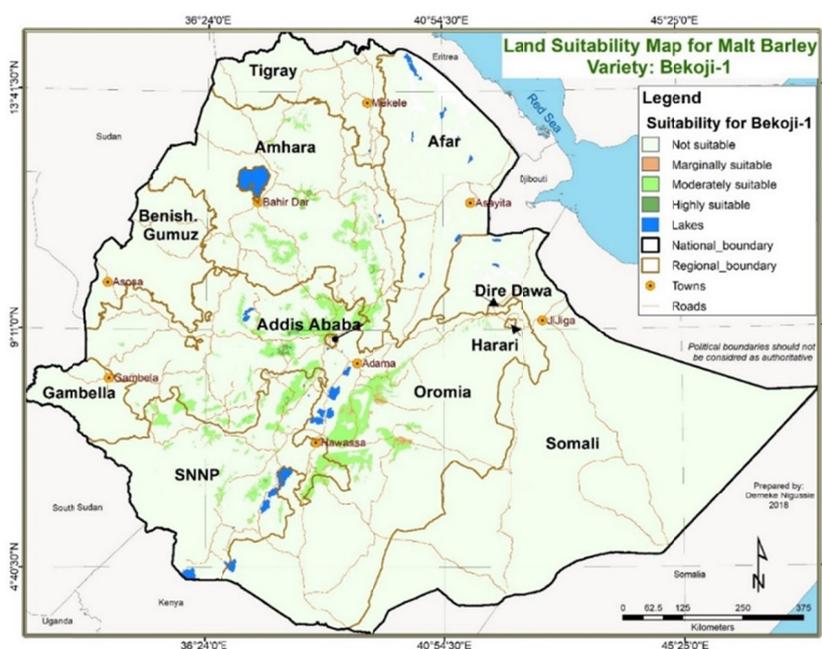


Figure 2. Land suitability map for malt barley variety Bekoji-1

3.2 Variety EH1847 [F4.2P.5.2 (Bea/IBON 64/91)]

EH1847 variety, like Bekoji-1 and Holker, is also a late-maturing and tall variety with the average yield potential of 3.5-4.4 t ha⁻¹ in research fields under recommended management (Table 1). The variety level suitability analysis and mapping results for this variety are presented in Table 6 and Figure 3. The analysis results showed that highly suitable land areas for variety EH1847 are the lowest (124,004 ha) as compared to that of other varieties analyzed in this work (Table 4). Late maturing varieties like EH1847 perform best in frost free long growing periods in the high altitude highlands of Ethiopia.

Table 6. Land area and suitability classes for malt barley variety EH1847 production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not Suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	35,280	0.23	860,068	5.53	4,776	0.03	14,663,245	94.22
Oromia	74,780	0.23	2,510,864	7.74	131,136	0.4	29,732,633	91.63
SNNP	13,944	0.12	953,844	8.45	38,348	0.34	10,283,850	91.09
Tigray	0	0	3,400	0.07	0	0	5,017,258	99.93
Afar	0	0	0	0	0	0	9,562,336	100
BSG	0	0	2,668	0.05	0	0	4,997,689	99.95
Gambella	0	0	88	0	0	0	2,570,048	100
Somali	0	0	0	0	0	0	31,561,965	100
Total	124,004	0.11	4,330,932	3.83	174,260	0.15	108,389,024	95.90

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

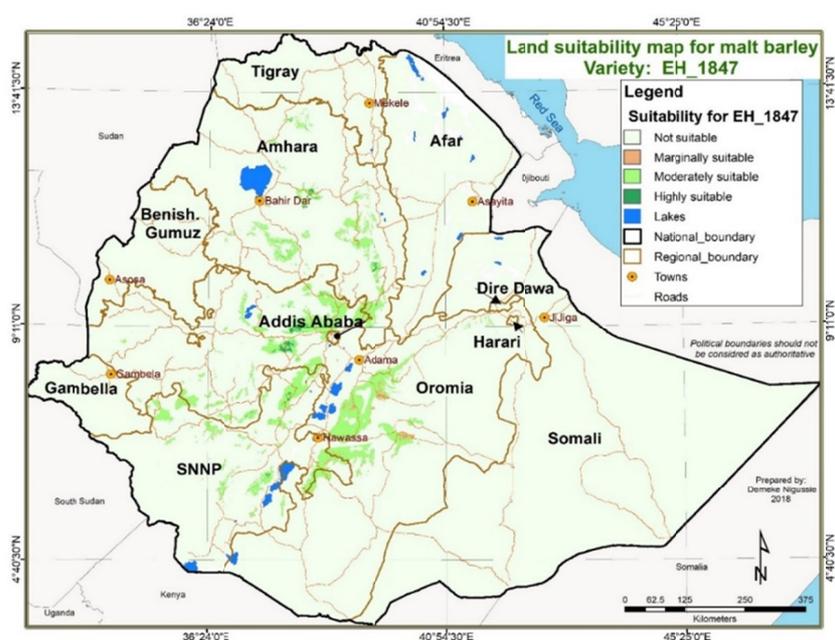


Figure 3. Land suitability map for malt barley variety EH1847

3.3 Variety Grace

Grace is an early maturing malt barley variety with the average yield potential of 2.0–4.0 t ha⁻¹ in research fields under recommended management (Table 1). The variety level suitability analysis and mapping results for this variety are presented in Table 7 and Figure 4. Being relatively early maturing and resistant to net blotch, the suitability analysis results for variety Grace show that it fits to the second largest highly suitable land areas of 775,312 ha when compared with other target varieties in Table 4.

Table 7. Land area and suitability classes for malt barley variety Grace production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not Suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	360,748	2.32	4,943,524	31.76	17,128	0.11	10,241,969	65.81
Oromia	359,520	1.11	11,363,196	35.02	163,200	0.5	20,563,497	63.37
SNNP	48,388	0.43	4,155,640	36.81	121,596	1.08	6,964,362	61.69
Tigray	6,640	0.13	45,428	0.9	0	0	4,968,590	98.96
Afar	0	0	108	0	0	0	9,562,228	100
BSG	16	0	108,048	2.16	1,072	0.02	4,891,221	97.82
Gambella	0	0	13,364	0.52	0	0	2,556,772	99.48
Somali	0	0	19,456	0.06	276	0	31,542,233	99.94
Total	775,312	0.69	20,648,764	18.27	303,272	0.27	91,290,872	80.78

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

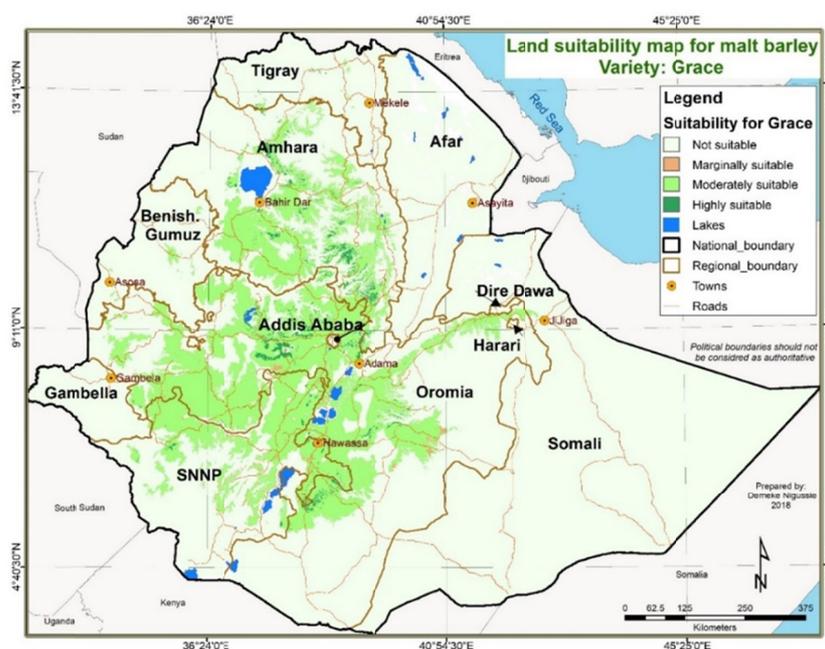


Figure 4. Land suitability map for malt barley variety Grace

3.4 Variety Holker

The variety level suitability analysis and mapping results for this variety are presented in Table 8 and Figure 5. Holker is like Bekoji-1 and EH1847 varieties is late maturing, its niche for expressing its potential is a frost free 125,356 ha of land with long growing period in high altitude highlands of Ethiopia.

Table 8. Land area and suitability classes for malt barley variety Holker production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not Suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	35,172	0.23	861,060	5.53	3,892	0.03	14,663,245	94.22
Oromia	75,484	0.23	2,514,372	7.75	127,356	0.39	29,732,201	91.63
SNNP	14,700	0.13	961,168	8.51	31,260	0.28	10,282,858	91.08
Tigray	0	0	3,400	0.07	0	0	5,017,258	99.93
Afar	0	0	0	0	0	0	9,562,336	100
BSG	0	0	2,668	0.05	0	0	4,997,689	99.95
Gambella	0	0	88	0	0	0	2,570,048	100
Somali	0	0	0	0	0	0	31,561,965	100
Total	125,356	0.11	4,342,756	3.84	162,508	0.14	108,387,600	95.90

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

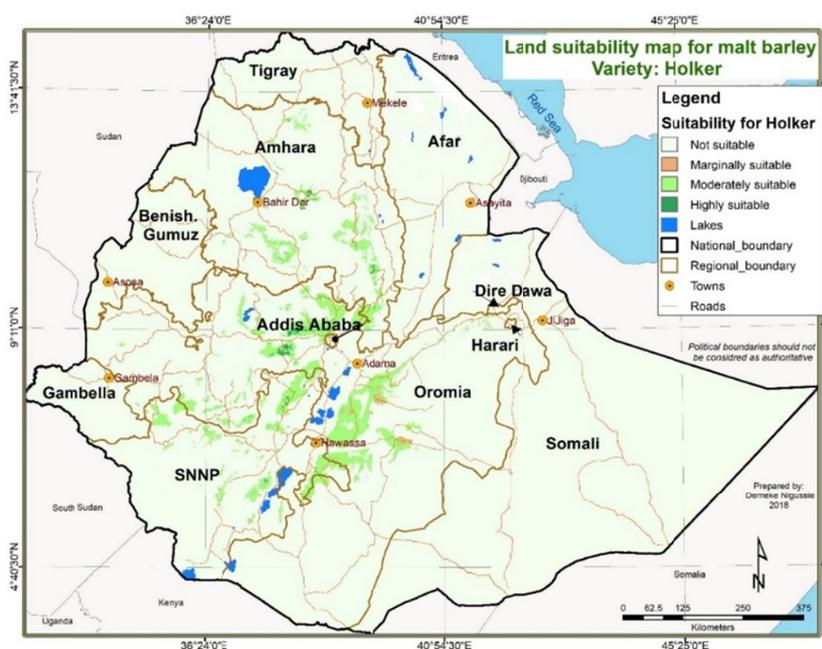


Figure 5. Land suitability map for malt barley variety Holker

3.5 Variety IBON 174/03

Average yield potential of variety IBON 174/03 was reported to be 3.0-5.7 t ha⁻¹ in research fields under recommended management (Table 1). It is tolerant to scald and resistant to leaf blotch. IBON 174/03 is also an early maturing variety escaping terminal stresses such as moisture deficit and relatively higher temperature in mid altitude areas, and frost damage in high altitude highlands of Ethiopia. Land suitability analysis and mapping results for this variety are shown in Table 9 and Figure 6. Its earliness and disease resistance helped it fit to the largest land area (1,677,388 ha) of highly suitable class as compared to other early and late maturing varieties (Table 4).

Table 9. Land area and suitability classes for malt barley variety IBON 174/03 production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not Suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	845,712	5.43	2,888,004	18.56	4,120	0.03	11,825,533	75.98
Oromia	738,680	2.28	6,108,104	18.82	17,440	0.05	25,585,189	78.85
SNNP	78,508	0.7	2,551,312	22.6	11,232	0.1	8,648,934	76.61
Tigray	8,044	0.16	3,608	0.07	0	0	5,009,006	99.77
Afar	0	0	0	0	0	0	9,562,336	100
BSG	6,444	0.13	33,160	0.66	0	0	4,960,753	99.21
Gambella	0	0	3,968	0.15	0	0	2,566,168	99.85
Somali	0	0	0	0	0	0	31,561,965	100
Total	1,677,388	1.48	11,588,156	10.25	32,792	0.03	99,719,884	88.23

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

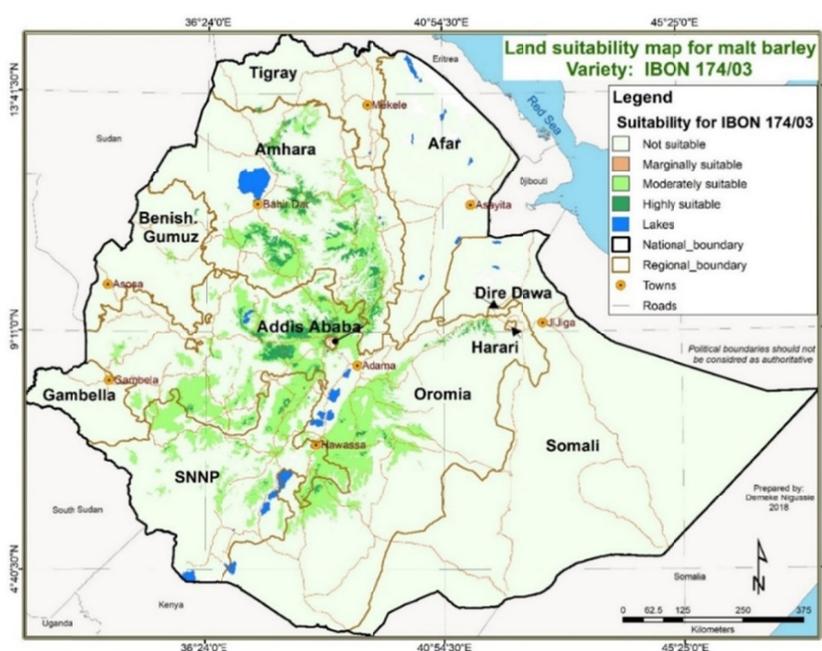


Figure 6. Land suitability map for malt barley variety IBON 174/03

3.6 Variety Sabini

Sabini is an early maturing variety with the average yield potential of 2.5-4.9 t ha⁻¹ in research fields under recommended management (Table 1). It is susceptible to scald in the high altitude highlands. Land suitability analysis and mapping results for this variety are presented in Table 10 and Figure 7. Susceptibility of variety Sabini to scald is tolerable since the negative effect on yield and grain quality for malt is negligible according to our unpublished observation during the implementation of USAID-ICARDA seed production and scaling project during 2015-2018. Therefore, its highly suitable land area (307,952 ha) was the third largest after that of IBON174/03 and Grace.

Table 10. Land area and suitability classes for malt barley variety Sabini production in Ethiopia

Regional states	Highly Suitable		Moderately Suitable		Marginally Suitable		Not suitable	
	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*	Area (ha)	%*
Amhara	101,588	0.65	4,236,844	27.22	36,812	0.24	11,188,125	71.89
Oromia	185,216	0.57	8,581,572	26.45	71,856	0.22	23,610,769	72.76
SNNP	19,840	0.18	3,450,676	30.56	79,660	0.71	7,739,810	68.55
Tigray	1,308	0.03	21,696	0.43	16	0	4,997,638	99.54
Afar	0	0	0	0	0	0	9,562,336	100
BSG	0	0	60,236	1.2	1,596	0.03	4,938,525	98.76
Gambella	0	0	7,308	0.28	0	0	2,562,828	99.72
Somali	0	0	16	0	8	0	31,561,941	100
Total	307,952	0.27	16,358,348	14.47	189,948	0.17	96,161,972	85.09

Note. SNNP = Southern Nations, Nationalities and Peoples; BSG = Benishangul-Gumuz; * % refers to percent area for each suitability class calculated against the total area for each Regional State.

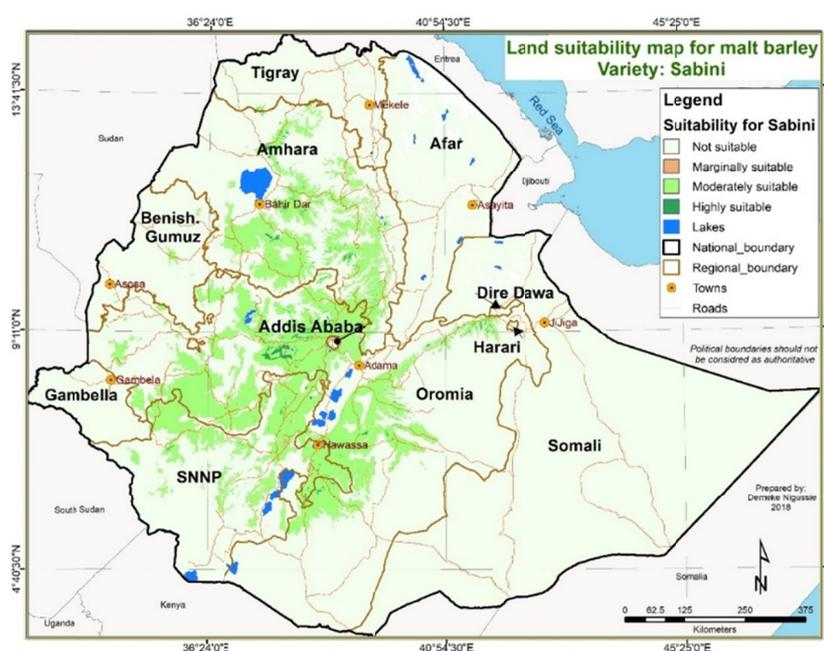


Figure 7. Land suitability map for malt barley variety Sabini

4. Discussions

The integrated land suitability analysis on altitude (largely influencing rainfall and temperature which are also major parameters of the analysis), length of growing period, soil type, soil texture, soil drainage, soil pH, soil depth, and slope showed that the size of highly suitable land areas are ranging from 124,004 to 125,356 ha for late maturing varieties (Bekoji-1, EH 1847 and Holker) which was by far smaller than that of early maturing varieties (Grace, IBON 174/03 and Sabini) having a range from 307,952 to 1,677,388 ha (Table 4). Physico-chemical grain quality parameters for malt were equally considered with productivity in our integrated land suitability analysis for malt barley production in Ethiopia. With this understanding, the major reasons for differences in size of suitable land share among target varieties are described below.

In Ethiopia, rainfall amount and length of growing period mostly increase with increasing altitude while temperature decreases (Hurni, 1998; MoA, 1998) and, therefore, late-maturing varieties mostly attain their higher productivity in high altitude highlands so long as excessive rainfall and terminal frost are avoided. Our unpublished field observations in high altitude highlands (above 2700 masl) during the implementation of USAID-ICARDA malt barley scaling project during 2015-2018 indicated that late maturing varieties Bekoji-1, EH 1847 and Holker express their higher yield potential when planted as soon as effective rainfall sets in from late May to mid-June in order to have a frost-free period during grain filling in late September to end of October.

Farmers also prefer these late maturing varieties due to their tall plant height which attributes to higher straw yield to feed livestock and weed suppression effects. Similar to Bekoji-1, EH1847 and Holker, malt barley varieties for the high altitude areas are required to be resistant to scald disease since the infection level of this disease increases with increasing altitude (MoA, 2010, 2011; Aynewa, Dessalegn, & Bayu, 2013).

Our mapping indicates that land area of altitudes lower than 1500, 1501-2400, and 2401-3200 masl, respectively constitute 65.91, 26.37 and 6.95% of the land area of Ethiopia with the corresponding annual average temperature of higher than 27.5, 20-16 and 16-11°C. In comparison to late maturing varieties, early maturing varieties are flexible enough to have larger land area share since they mature early to escape high temperature and rainfall stresses which are limiting malt barley productivity and grain quality. Production of some early maturing varieties may marginally extend up to 3201-3500 masl covering 0.49% land share of the country while no production land area above 3500 masl covers 0.29%. Highly suitable land areas for late maturing varieties are in 2600-3000 masl while those of early maturing varieties are in 2000-3000 masl (Table 3). Days to maturity generally increase with increasing altitudes. Higher altitudes with more than 160 days of growing period are difficult for early maturing varieties to harvest and dry unless there are dry spell periods. This extended length of growing period may cause sprouting in the field and spoil grain quality of matured early maturing varieties unless there are mechanized harvesting in a window of dry spells and grain drying facilities. If these facilities are in place, early maturing varieties open an opportunity for double cropping in high altitudes with extra-long growing periods.

Soil acidity which increases with increasing rainfall which in turn largely increases with increasing altitude also limits malt barley productivity and grain quality since availability and toxicity of micronutrients such as aluminum, manganese and iron increases as the pH decreases. A field experiment elsewhere in southern Ethiopia indicated that barley grain yield productivity of about 1023, 1264, 1772 and 2017 kg ha⁻¹ on the respective soil pH of 4.8, 5.2, 5.7 and 6.3 in areas with 2650-2900 masl receiving average annual rainfall of 1000-1300 mm (Boke & Fekadu, 2019). Again, land share of late maturing varieties which are developed for high altitude highlands of above 2400 masl is limited by the associated lower soil pH. According to the review by Abate, Hussein, Laing, and Mengistu (2016), acid soils with a pH of below 5.5 in the surface layer constitute about 13.2% of the total land in Ethiopia, which could be 34,931,776 ha in our mapping. Improving productivity of this acidic land area requires huge investment to meet lime application recommendation of more than 6 t ha⁻¹ for soil with less than 4.5 pH; and 4-5 t ha⁻¹ for soil with 4.5-5.5 pH in broadcast application every 5 years though band application reduces the rate by half (Tilahun, Schulz, Warner & Solomon, 2019). Therefore, to reduce the rate of this huge lime application requirement, breeding to develop acidic soil tolerant malt barley varieties is an important research area in Ethiopia since there is high probability of success as the Brazilian experience shows (Bian et al., 2015).

The latest review by Merga and Ahmed (2019) indicated that Vertisols cover a total area of 12.6 million ha (10.3%) of the soils in Ethiopia of which more than 60% is in the highlands where they are most frequent on the 0-2% slope range. Because of limited internal drainage, in Ethiopia, the tremendous potential of Vertisols for crop production is severely constrained by waterlogging leading to yield reduction and negatively affecting physical (grain size, plumpness, test weight) and chemical (increasing protein while reducing starch content) quality in malt barley. The highlands cover altitudes of ≥ 1500 masl having an area of 7,560,000 ha of Vertisols. Intensity of waterlogging increases with increasing altitude since rainfall mostly increases while temperature decreases with increasing altitudes. Review of worldwide experiences show that barley is more susceptible to waterlogging stress than other cereals, and waterlogging in general and on Vertisols in particular is a major limiting factor for barley production (Bertholdsson, 2013). Therefore, having such large area of land in the Ethiopian highlands, Vertisols are marginally suitable for barley production in general and for malt barley in particular since malt barley, as compared to food barley, grows slowly at early stage and waterlogging stresses spoil grain quality. However, worldwide experiences in breeding for waterlogging tolerance (Bertholdsson, 2013) and the available diversity of barley in the Ethiopian highlands (Hadado, Rau, Bitocchi, & Papa, 2010) are important inputs to start the breeding program at least to reclaim this vast resource for seed production where chemical grain quality of malt barley is not a priority.

Soil depth and slope are interrelated parameters which all together affect soil water holding capacity thereby length of growing period of malt barley. Generally, soil depth decreases while slope (because of ruggedness of the highlands) increases with increasing altitude because of increasing soil erosion associated with increasing rainfall and ruggedness. Because of these scenarios, soil erosion, which significantly reduces soil depth, is a serious soil degradation factor in the highlands of Ethiopia where the recent study reported soil losses of 0 in plain areas to 237 t ha⁻¹ year⁻¹ in the steep slopes (Gashaw, Tulu, & Argaw, 2017). Because of direct physical soil

loss by erosion on higher slopes in the highlands of Ethiopia, soil clay, pH, cation exchange capacity, exchangeable Ca, Mg, extractable Mn, Zn, Fe, and Cu generally showed a decreasing trend with increasing slope gradient (Jembere, Mamo, & Kibret, 2017). Estimates through modeling work also suggests that soil erosion in Ethiopia reduces the potential production of the land by 10% in 2010 and by 30% in 2030. As a result, the value added per capita per annum in the agricultural sector will go down from US\$372 in 2010 to US\$162 in 2030 (Gashaw et al., 2017, citing Sonneveld & Keyzer, 2003). This is again additional huge challenge for Ethiopia to improve productivity and production of crops in general and malt barley in particular as it needs highly suitable land areas for maintaining both productivity and grain quality for breweries.

Therefore, our integrated multi-layer land suitability analysis and mapping show that early maturing malt barley varieties have larger highly and moderately suitable land area shares as compared to the late maturing varieties which have narrow niche, usually in high altitude highlands. Moderately suitable land areas may need additional interventions on top of the recommended production packages of malt barley production. According to the recent report on the results of nationwide soil and water conservation measures which have been going on for decades in the rugged highlands resulted in significant improvements in the agronomic and economic efficiency of productivity enhancing technologies (Biru, Zeller, & Loos, 2020).

In the final analysis, this work is a national level and broad scale integrated multi-criteria land suitability analysis without considering irrigation potentials and socio-economic aspects. Amhara, Oromia, SNNP and Tigray Regional States remain the major regions with suitable land areas for production of available varieties of malt barley compared to Afar, Benishangul Gumuz, Gambella, and Somali Regional States. Oromia Regional State has more highly suitable and moderately suitable land areas than other regional states. However, the highly suitable land areas are limited compared to moderately suitable ones, which are higher across the regional states. For the malt barley varieties considered in this analysis, the highly suitable land areas were found to be much smaller than the current estimated area under barley production in the country and crop level suitability except for one variety. IBON 174/03 has the highest overall highly suitable area of 1.7 million ha which is close to the crop suitability level followed by Grace with 0.8 million ha and Sabini with 0.3 million ha. Oromia Regional State has the highest moderately suitable land area for malt barley of which Grace, Sabini and IBON 174/03 has a share of up to 35.02%, 26.45% and 18.82%, respectively.

5. Conclusions and Recommendations

5.1 Conclusions

Although this work is a broad scale nationwide integrated multi-criteria suitability analysis, which is only based on biophysical factors, it is intended to serve as a guide for agricultural research and development related policy and decision-making at broad scale (national level). The analysis clearly showed that, as compared to late maturing malt barley varieties, early maturing ones have larger niches of highly and moderately suitable land areas and should receive more attention to improve productivity and production of malt barley in the highlands of Ethiopia. In addition to identifying and mapping different land suitability classes for malt barley production in Ethiopia, we have also shown priority research and development areas to improve productivity of acidic and waterlogging soils as well as soil and water conservation works to improve natural resource base potential for enhancing agronomic and economically efficient responses to application of improved crop technologies.

5.2 Recommendations

It is recommended to undertake site-specific analysis and to map the key parameters at higher spatial details to better understand the granularity and level of scaling-up of the specific crop technology for targeting location specific recommendation at farm to farming systems level. Data on performance of crop varieties across a wide range of representative environments are very scanty and need future attention. The organizations that are involved in improving soil, land use/land cover, and climate information at national level need to produce high-resolution and reliable information that could be used for site-specific spatial and simulation modelling for agricultural application. Furthermore, researchers involved in crop improvements also need to be able to use these suitability analysis results as a general guide in their research targeting decisions and feedback on performance of the crops for further refinement. However, farmers know their farm plots and therefore we can use their knowledge for avoiding shallow depth soils, frost frequented landforms and unproductive soils to make our results applicable at farm level. Therefore, the integrated multi-criteria suitability analysis results suggest that currently available improved malt barley varieties can be targeted for scaling out in the identified land suitability classes in the highlands of Ethiopia.

It is also suggested that researchers need to develop, update and have detailed documents elaborating information on environmental requirements for the different crops and varieties for suitability analysis, mapping and

simulation modelling based on recent research findings, particularly when new varieties are released. We also recommend leveraging recent advances in Earth Observation, Bigdata and ICTs for demand-driven decision support system for targeting site-specific intervention and smart farming for building resilient agroecosystems.

Currently available breeding technologies, experiences elsewhere and the high barley diversity we have in the highlands of Ethiopia suggest that breeding for developing early maturing, acidic soil and waterlogging tolerant malt barley varieties are important research areas which should receive attention.

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