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The decrease of potential suitable areas and the distribution tendency of staple crops in Ethiopia under future climate conditions

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Rain-fed agriculture is the most common pattern for Ethiopian smallholders, while it is sensitive to climate change in the future. In order to predict the impact of climate change and decrease the risk of food crisis in Ethiopia, the potential crops suitability of teff (*Eragrostis tef*), maize (*Zea mays*), wheat (*Triticum aestivum* Linn.) were simulated and suitable distribution were analyzed by using GIS-MCE (Multi-Criteria Evaluation) Planting Ecological Adaptability model under both current and future (2080s) climate conditions. The simulation showed that climate change will decrease the 14% potential suitable areas of teff from 41 to 27% and also reduce that of wheat from 33 to 29% in the future, while the potential suitable regions for maize will remain almost stable, or even slightly more (1%) in the future (46%) compared to the current conditions (45%). Overall, agriculture will suffer negative impacts on the main crops in Ethiopia. All these three crops' potential suitable lands are gathering to higher altitude which is in the centre of the whole nation because of warmer temperature. Thus, maize may become more widely grown and compete for lands with teff and wheat in high and mid-altitude. In this study, our model results can help both the policymakers and the smallholders to amend the existing limitations, as well as to plan better long-term strategies under the future climate scenarios.

Key words: Climate change, Ethiopia, geographical information system, multi-criteria evaluation, potential suitability.

INTRODUCTION

Reductions in agricultural production caused by future climate change could seriously weaken food security and worsen the livelihood conditions in most developing countries (Franks, 2005). Climate changes cause 46% of the cultivated areas in the world and are not suitable for rain fed agriculture (Valipour, 2015). Particularly, many countries in Africa were suffered by climate changes and supreme weather events (Deressa and Hassan, 2009). The IPCC (2007) demonstrated that warming is supposed to be greater than global average in sub-

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Saharan Africa which is likely to exceed 3°C over next century (Parry et al., 2007; Thompson et al., 2010) and the rainfall in parts of these area will decline (Bryan et al., 2009). In sub-Saharan Africa countries, most of the countries relying on rain-fed farming will face the great threat that land area available for agriculture is limited (Herrero et al., 2012; Thompson et al., 2010). The amount of water-managed areas as share of cultivated areas in Africa is significantly lower than the world, this signifies that water management is particularly poorly in rainfed cultivated areas (Valipour, 2013). Therefore, Ethiopia will be suffered more from changing climate scenarios as it is a typical sub-Saharan country and lack effective strategies to cope with agricultural change caused by climate variable (Thompson et al., 2010; Washington et al., 2012).

Ethiopia is a tropical land-locked country in East Africa with high levels of population density. Although agriculture makes a great contribution to the Ethiopian GDP and four-fifths of the population live in rural areas that rely on agriculture-related industries (Diao et al., 2010), most of agriculture is under rain-fed condition in Ethiopia engaged by small farm management form (Araya et al., 2010). Besides, owing to the poor knowledge about agricultural water requirement, irrigation efficiency is low and crops are under water stress (Valipour, 2012). It is critical in light of low crop productivity dominantly in Ethiopian agriculture, which causes chronic food insecurity with recurrent drought and rapid population growth (Gebre-Selassie and Bekele; Hordofa et al., 2008; Taffesse, 2008). For centuries, the principal grains, overriding three cereals – teff, maize and wheat, have fed peasant farmers and their communities in Ethiopia (Se et al., 2012; Yumbya et al., 2014). These staple cereals are the foremost component in the most Ethiopians' diet and also the key to food security in rural Africa. However, the effects of climactic changes on these three crops' suitability are varied and not fully understood.

Teff is an annual grass which is widely cultivated throughout the whole Ethiopia and accounts for about a quarter of the Ethiopian total grain output. The most preferred staple food Injera, traditionally made out of teff flour, is a national dish which is unique in Ethiopia and Eritrea (Chamberlin and Schmidt, 2012; Girma and Ababa, 2010). Maize is also a major crop in Ethiopia. It is a kind of warm-weather grain widely cultivated and grown mostly at lower altitudes. Besides, maize is second only to teff in cultivated area coverage, but first in total production among all the cereals (Worku et al., 2012). For wheat, Ethiopia is the largest wheat producer in sub-Saharan Africa (Mariam, 1991). The Ministry of Agriculture of Ethiopia (2002) shows that wheat is one of the most general cereals which have grown predominantly in the Ethiopian highlands and cultivated merely under rain-fed conditions.

This paper analyzes potential suitable distribution of staple crops in Ethiopia under both current and future climate conditions and aims to provide information for appropriate adaptive policies at national or regional level so as to minimize the adverse impacts of climate change on agriculture. In this study, the climate and geographical data (input data) are combined and transformed into a consequent decision (output) using the GIS-MCE model. Finally, the potential suitable level of Ethiopia agriculture under both current and future climate conditions are simulated and evaluated.

Our objectives were to: (1) grade the climatic suitability of teff, maize and wheat planting distribution under current climate conditions in Ethiopia; (2) simulate and predict the suitable cultivation regions of teff, maize and wheat under future (2080s) climate conditions; (3) further analyze the tendency of these three crops suitability and the variability of cultivating structure primarily owing to climate changes. It is expected that the study can provide crop planning strategies, improve land use and promote the sustainable development of agriculture which adapt to climate changes in the circumstance of national scale.

MATERIALS AND METHODS

Study area

Ethiopia lies from longitudes 33°E to 55°E and latitudes from 3.5°N to 15°N, covering a land area of 1.13 million km² and including large areas of flat land and gently rolling hilly areas as well as steep mountains and ragged valleys. There is an uneven distribution among regions, mainly varies with regional altitude changes from slightly below sea level to more than 4,000 m above sea level (Figure 1). Thus, the climate of Ethiopia is quite variable across the country. Ethiopia's climate is mainly tropical steppe climate and subtropical forest climate, the annual average temperature is from 10 to 27°C and the tropical zone receives less than 510 mm rain per annum, while the subtropical zone, which includes most of the highlands, receives 510 to 1,530 mm of rain annually (Mati, 2006).

Despite it is difficult to make agricultural planning due to variable rainfall, a large proportion of the Ethiopia gets sufficient for rain-fed crop production. In the north of the country, the rainfall pattern is mainly bimodal, with the shorter starts around March/April and the second one begins around June/July. In some regions, the two seasons combine into a unimodal pattern, which the main crop planting season is from June to October and it almost depends on rain. The main crops in Ethiopia are teff (*Eragrostis tef*), maize (*Zea mays*) and wheat (*Triticum aestivum* Linn.), etc.

Meteorological data and climate index

Considering meteorological data is vital to the distribution of cultivation areas, we choose several climate indexs, including: a) accumulative daily mean temperature (AT); b) monthly average maximum temperature (T-max); c) monthly average minimum temperature (T-min); d) monthly precipitation (PRE) (Doss et al., 2003; Feleke and Zegeye, 2006; Laekemariam et al., 2012; Mariam, 1991; Tesemma et al., 1998).

Meteorological data, both under current and future conditions, are downloaded from the Website of World Clim-Global Climate Data (http://www.worldclim.org). The future conditions (2080s) data is global climate model (GCM) data from Fourth Coupled Model Intercomparison Project (CMIP4) (Parry et al., 2007; Solomon, 2007). Coupled Global Climate Model (CGCM3) was selected

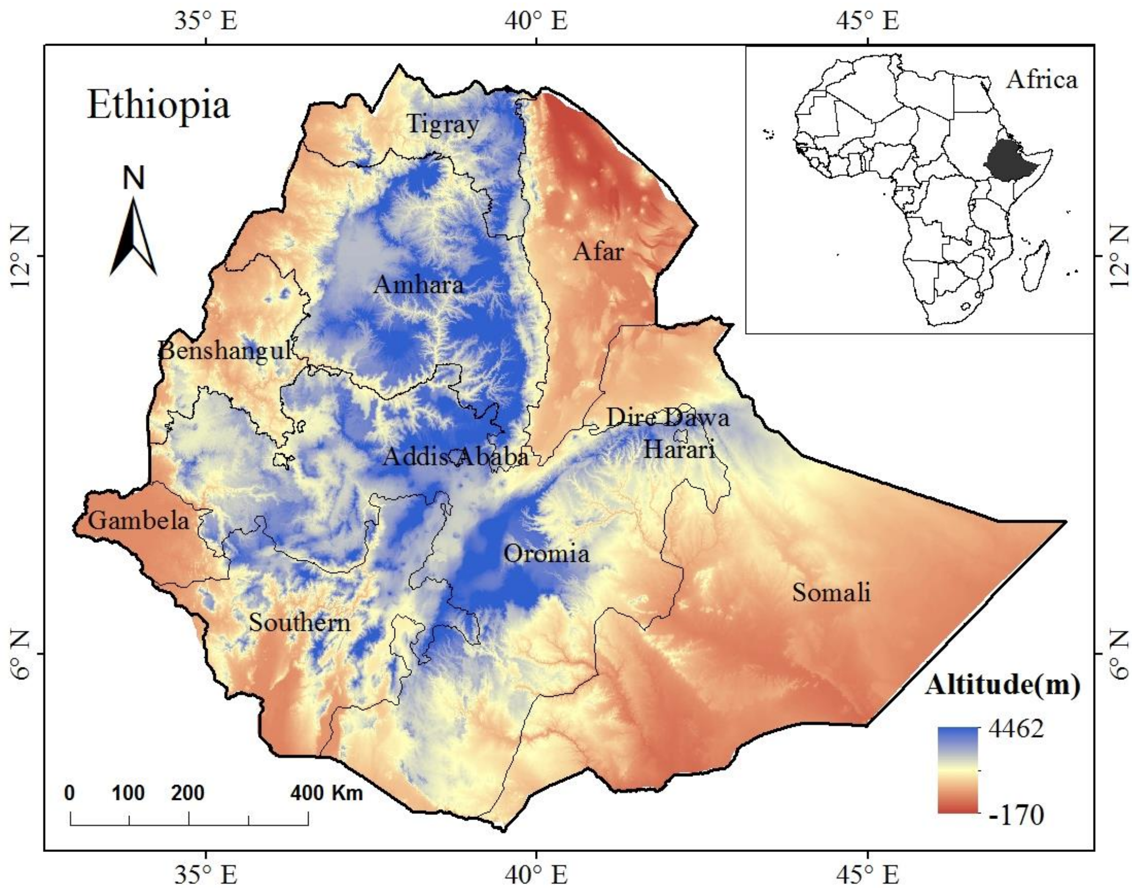

Figure 1. Altitude and provincial boundary of Ethiopia.

under SRA1B emission scenarios as our model, developed by Canadian Centre for Climate Modeling and Analysis (CCCma) (Solomon, 2007). The A1 family scenarios are distinguished by their technological emphasis in an alternative directions of energy system and they are divided into three groups (A1FI, A1B, A1T). A1B scenario is not only relying heavily on one particular energy source and it assume that similar improvement rates are applied to all end-use technologies and energy supply (Gaffin et al., 2004; Parry et al., 2007).

The resolution of this data is 30 s and it can be used for many research field, such as agriculture, environment and life sciences, etc. It simulates to the future conditions well in seasonality of temperature and precipitation patterns especially for the sub-Saharan Africa (Washington et al., 2012).

Elevation and soil data

The Digital Elevation Modal (DEM) in this study is downloaded from ASTER GDEM which is available online (http://www.jspacesystems.or.jp/ersdac/GDEM/E/4.html). The resolution of this data is 30 m.

The soil data contains soil pH and soil texture data, which is selected from Harmonized World Soil Database (http://webarchive.iiasa.ac.at/Research/LUC/External-World-soil-database/HTML/). The field moisture capacity (FMC) data is calculated by using the following equation (Gupta and Larson, 1979):

$$FMC = 0.008039 \times Cl + 0.005886 \times Si + 0.003075 \times Sa + 0.002208 \times SOM - 0.1434 \times BD.$$

where FMC: field moisture capacity; Cl: soil clay content (%); Si: soil silt content (%); Sa: soil sand content (%), the US system; SOM: soil organic matter content (%); BD: soil bulk density (g/cm^3).

Planting ecological adaptability model based on GIS-MCE

Planting ecological adaptability model plays a vital role in predicting the distribution of crops and evaluating crop adaptability (Ceballos-Silva and Lopez-Blanco, 2003; He et al., 2014; Jia et al., 2014; Malczewski, 2004). It is usually based on geographical information system (GIS). The multi-criteria evaluation (MCE) can be seen as a method that transforms and combines spatial geographical data (input) into a resultant decision (output) (Cobuloglu and Büyüktahtakın, 2015). The flow chart of GIS-MCE procedure is as shown in Figure 2.

Firstly, according to the eight meteorological data (elevation, monthly mean temperature-max (T-max), monthly mean temperature-min (T-min), accumulative temperature (AT), monthly precipitation (PRE), soil pH, soil texture and field moisture capacity (FMC)), several thematic layers were created by using GIS. In this study, we adopted FAO system which classifies land suitability rating based on meteorological and soil indices. The indices were classified into five levels which represent very high, high, medium,

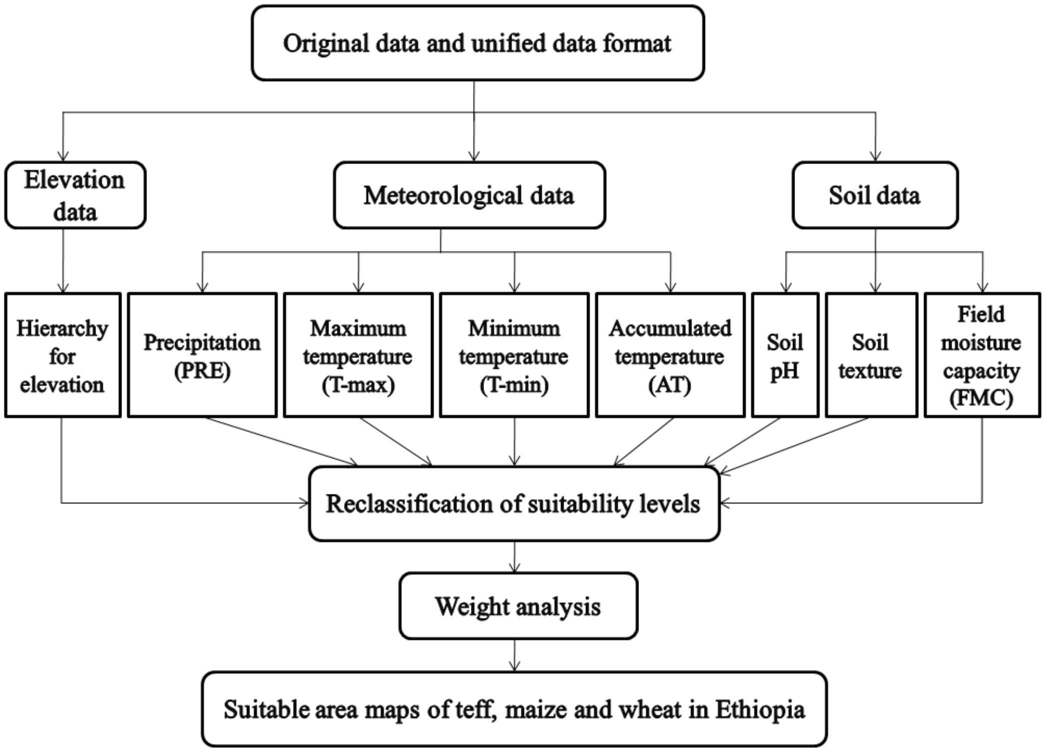

Figure 2. Procedures of GIS-MCE Planting Ecological Adaptability model.

Table 1. Each index suitability level classification for teff in Ethiopia.

Index	Level of suitability				
	Most suitable	**Moderate suitable**	**Medium**	**Moderate unsuitable**	**Unsuitable**
Accumulative temperature ≥10°C	2700-3800	3800-4500	4500-5500	1500-2700 or >5500	<1500
Precipitation (mm)	900-1400	600-900	1400-1800	350-600 or >1800	<350
Max Temp (°C)	26.5-29	25-26.5	29-31	31-34	>34 or <25
Min Temp (°C)	9-12	12-16	6-9	>16	<6
Field moisture capacity (%)	0.45-0.54	0.54-0.6	0. 3-0.45	0.25-0.3 or >0.6	<0.25
Soil pH	6.2-7.4	5.0-6.2	7.4-8.5	<5.0	>8.5
Elevation (m)	1800-2200	1500-1800	950-1500	2200-2950 or <950	>2950
Soil texture	clay	loam	Sand	Other class	none

low, and very low (Kalogirou, 2002). And each suitability level was defined by literature reviews and experts' suggestions (Araya et al., 2011; Easterly, 2002; Kebede et al., 2012; Mati, 2006; Temesgen et al., 2008) (Tables 1 to 3).

Secondly, the weight of each index was calculated by analytical hierarchy process (AHP) using pair-wise comparison matrix. The rating process was operated on a nine-point scale and the relative importance of every two indices regarding the land suitability was compared. The weight coefficient of each crop was calculated by MATLAB software and its value ranged from 1 to 9/9 (Hoogenboom, 2000; Masilionytė and Maikštėnienė, 2011; Sultan et al., 2013; Tadross et al., 2009; Turner and Rao, 2013 (Table 4).

Eventually, the data in the GIS were organized by several thematic maps (Figure 3). Different thematic layers were merged into maps and the potential suitability level of each crop was simulated by using indices and weight characters.

RESULTS

Simulation of teff potential suitable growing areas under both current and future climate conditions

Under current climate conditions, teff is widely suitable including moderate and the most suitable region located in the central and northern part of Ethiopia (Figure 4), which occupies approximately 41% area of the whole country (Table 5). Accompany with the temperature increase and the precipitation change in the future, teff's suitable and the most suitable areas will decrease from 41 to 27% and condense to much higher altitude. Moderate unsuitable areas for teff will mainly move to the

Table 2. Each index suitability level classification for maize in Ethiopia.

Index	Level of suitability				
	Most suitable	Moderate suitable	Medium	Moderate unsuitable	Unsuitable
Accumulative temperature ≥10°C	2500-3600	3600-4200	4200-5000	1000-2500	<1000 or >5000
Precipitation (mm)	800-1200	1200-1500	1500-1700 or 500-800	>1700	<500
Max Temp (°C)	20-25	25-31	15-20 or 31-35	>35	<15
Min Temp (°C)	10-17	17-20	0-10	>20	<0
Field moisture capacity (%)	0.37-0.46	0.46-0.55	0. 3-0.37	0.18-0.3 or >0.55	<0.18
Soil pH	6.5-7.0	5.0-6.5	7.0-8.0	<5.0	>8.0
Elevation (m)	1000-1500	1500-2000	600-1000 or 2000-2300	>2300	<600
Soil texture	Loam	Sand	Clay	Other class	none

Table 3. Each index suitability level classification for wheat in Ethiopia.

Index	Level of suitability				
	Most suitable	Moderate suitable	Medium	Moderate unsuitable	Unsuitable
Accumulative temperature ≥10°C	2400-3100	3100-4000	4000-5200	1500-2400 or >5200	<1500
Precipitation (mm)	600-1200	1200-1700	>1700	350-600	<350
Max Temp (°C)	21-23	23-25.5 or 19-21	19-21	25.5-30	<19 or >30
Min Temp (°C)	6-9.3	9.3-11	2-6 or 11-15	>15	<2
Field moisture capacity (%)	0.4-0.52	0.52-0.6	0. 35-0.4	0.25-0.35 or >0.6	<0.25
Soil pH	6.5-7.0	7.0-7.5	7.5-8.5	<6.0	>8.5
Elevation (m)	1500-2300	800-1500	2300-2700	2700-3000 or <800	>3000
Soil texture	Loam	clay	Sand	Other class	none

Table 4. Weight coefficient of each index using AHP calculated.

Crop	Index								
	Elevation	PRE	T-max	T-min	AT	Soil pH	Soil texture	FMC	total
Teff	0.0684	0.2045	0.1363	0.1591	0.1818	0.0454	0.0909	0.1136	1
Maize	0.0454	0.2045	0.1591	0.1364	0.1818	0.0628	0.0909	0.1136	1
Wheat	0.0684	0.2045	0.1363	0.1591	0.1818	0.0454	0.0909	0.1136	1

south of Oromia province and most areas of moderate unsuitable part, especially in the south of Afar and the whole Somali province, are turning to the most unsuitable regions (Figure 4). Thus, the proportion of most unsuitable area soars from 16 to 38% of the nation (Table 5).

Simulation of maize potential suitable growing areas under both current and future climate conditions

Under the current climate scenarios, both moderate and the most suitable distribution of maize is about 45% in total which is located in the west of the country, nearly half of the Ethiopia. In contrast, unsuitable area only accounts for one fourth of the nation (Table 6). Under the future conditions, except for Somali province becomes more unsuitable, the suitability of maize shows a decreasing tendency in Tigray province and demonstrates a rising trend in the south of Oromia province, which presents a southward tendency of suitable area (Figure 5).

Although the warmer temperature and changing rainfall will decrease the most suitable areas about 4% (from 23 to 19%), the moderate suitable areas will increase about 5% (from 22 to 27%) of the total areas (Table 6). That means, the suitable regions for growing maize, both moderate and the most, will remain almost stable, or even slightly more (1%) in the future (46%) compared to the current conditions (45%).

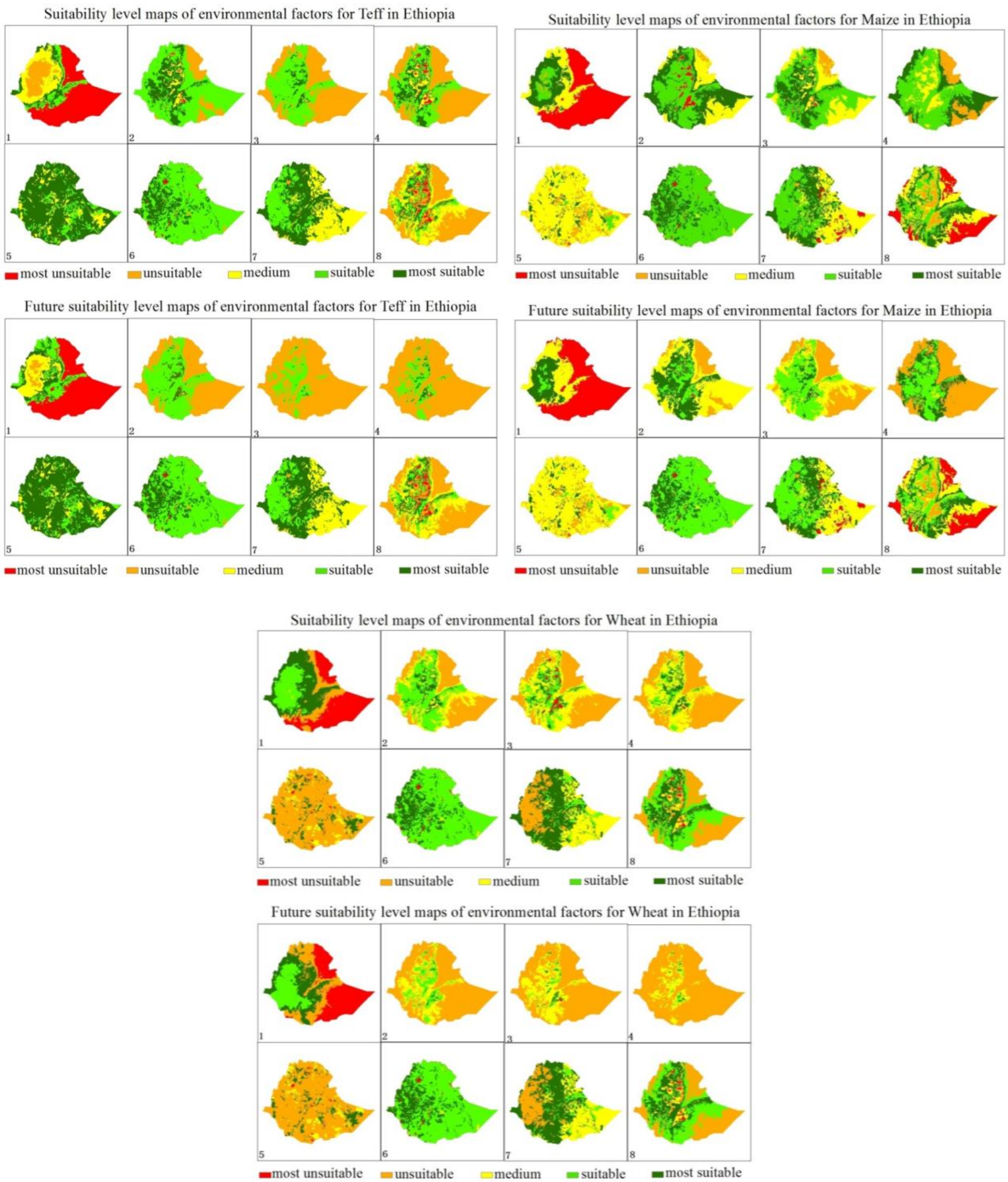

Figure 3. Suitability level maps of eight thematic factors for teff, maize and wheat under the current and future conditions (1 monthly precipitation (PRE); 2 accumulative temperature (AT); 3 mean maximum temperature (T-max); 4 mean minimum temperature (T-min); 5 field moisture capacity (FMC); 6 soil texture; 7 soil pH; 8 elevation).

Simulation of wheat potential suitable growing areas under both current and future climate conditions

Compare to the current conditions, there is no obvious changes for wheat among each suitable level in the future. The total proportion of unsuitable area, including both the most and moderate levels, rises slightly from 45 to 49%, while the medium one will level off at 22% of the whole Ethiopia. With the climate changes in the future, the proportion of the most suitable and moderate suitable

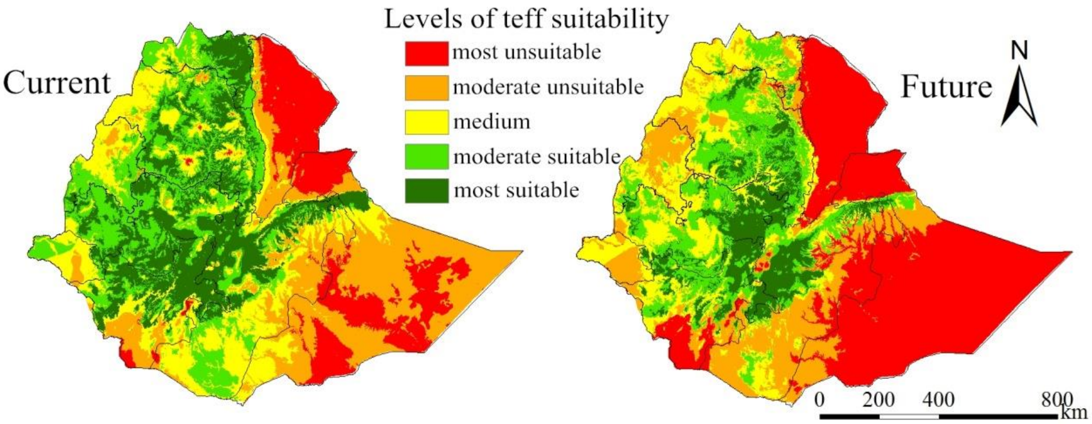

Figure 4. Potential suitable distribution areas of teff under both current and future conditions.

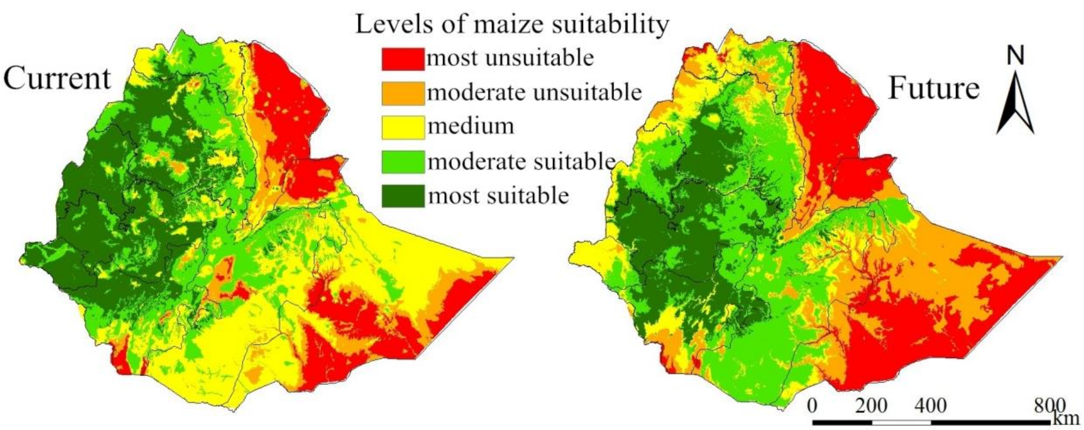

Figure 5. Potential suitable distribution areas of maize under both current and future conditions.

Table 6. Proportion of maize suitable levels under both current and future conditions in Ethiopia.

Parameter	Suitable levels				
	Most insuitable	**Moderate insuitable**	**Medium**	**Moderate suitable**	**Most suitable**
Current conditions (%)	15	10	30	22	23
Future conditions (%)	21	20	13	27	19

decreases 2% respectively, and its suitable area even more centralizes to higher altitude (Table 7).

DISCUSSION

Teff can be grown with a wide range of altitudes from near sea level to over 3000 m (Mekonnen et al., 2013). For the teff in Ethiopia, it is grown in the highlands at the best performance between 1800 and 2400 m, because it is a cool-resistant crop (Yumbya et al., 2014). And the average annual precipitation in teff-growing areas is 1000 mm, with a range of 300 to 2500 mm (Mekonnen et al., 2013). Primarily, due to the increasing temperature and the varying rainfall, the suitable areas for teff will be centralized to the plateau of Ethiopia in 2080s. Maize is grown chiefly at approximately 1500 to 2000 m in southern, south-central, and southwestern parts of Ethiopia (Abate et al., 2015). The most suitable planting area of maize is simulated at lower altitudes along the

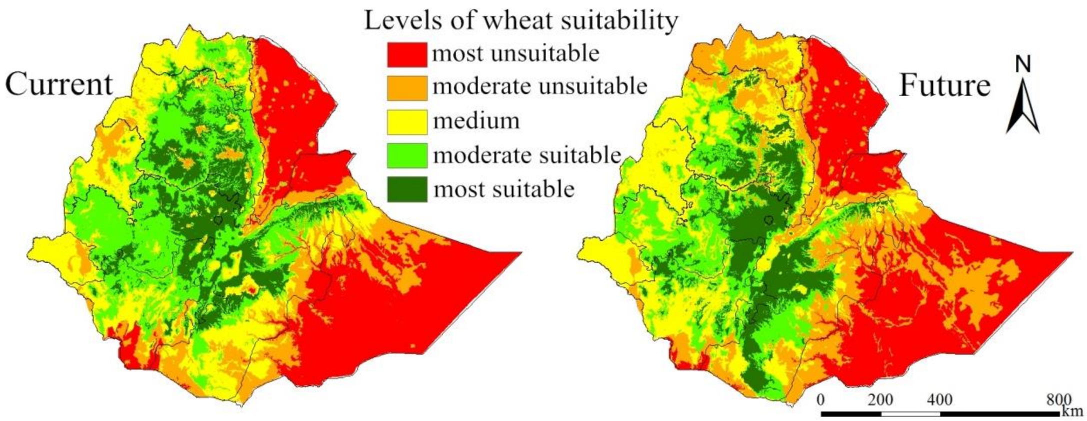

Figure 6. Potential suitable distribution areas of wheat under both current and future conditions.

Table 7. Proportion of wheat suitable levels under both current and future conditions in Ethiopia.

Parameter	Suitable levels				
	Most unsuitable	Moderate unsuitable	Medium	Moderate suitable	Most suitable
Current conditions	30	15	22	18	15
Future conditions	27	22	22	16	13

country's western peripheries under the current conditions. However, it is moving eastward and also competing for lands with teff and wheat in the high and mid-altitudes (Figure 5). For wheat in Ethiopia, it is an important cool-weather crop predominantly in highlands which is typically produced at the altitudes of 1600 to 3200 m (Chamberlin and Schmidt, 2012). And the average annual rainfall required for wheat is 400 to 1200 mm with the average annual temperatures of 15 to 25°C (Mekonnen et al., 2013).

There is a generally consensus that in the tropical and sub-tropical climatic zones, most of the crops' suitability decreased as the warming trend of climate change (Turner and Rao, 2013). If increased temperature is above the threshold of crops, it will lead to the death of crops (Thornton et al., 2009). In addition, evapotranspiration (ET) is one of the major components of the hydrologic cycle and it is supreme important for many investigations such as irrigation scheduling, crop yield simulation and farm management, particularly in arid environments (Khoshravesh et al., 2015; Valipour, 2014a, b). Thus, higher temperature and erratic rainfall will be expected to have a negative influence on the suitability of these three crops (teff, maize, wheat) (Figures 4, 5, and 6) through decreasing their growth and duration (Gregory et al., 2005). Under the future climate conditions, the increasing trend of temperature is projected continuously to be +0.03°C year^{-1} (Jury and Funk, 2013). Altitude plays a vital role in the distribution of crops as its impact of temperature (Mariam, 1991). The simulated result is in agreement with the IPCC report that suitable altitude of crops will move up 100 m when the temperature rises 1°C (Alexander, 2013). Different from teff and wheat, maize is a common warm-weather cereal and it is less tolerant of cold (Chamberlin and Schmidt, 2012; Yumbya et al., 2014). Crops with cooler optimal thresholds (such as teff and wheat) may be adversely affected by higher temperatures. Teff can be planted up to 2800 m, while limited production of maize occurs above 2400 m (Chamberlin and Schmidt, 2012). Although there is a common feature of these three crops' potential suitability, that is, the most suitable areas are all gathering to high altitudes, maize is becoming more widely grown throughout Ethiopia.

Teff has always occupied the biggest share of cultivated crop area since the start of national agricultural statistics in 1960s. However, the share of teff lands has gradually decreased by 5.8 percent over the past five decades from the 1960 to 2000s, by contrast, the share of maize areas has increased by 7.8%, while wheat remained relatively stable over this time (Se et al., 2012). In addition, maize was also the single most significant cereal in term of the number of small landholders involved in cultivation (Worku et al., 2012). It is interesting to notice that, different from the cultivated area, production growth was faster than the expansion of acreages during this period. The annual average growth of maize production was the fastest, followed by teff yield (Se et al., 2012). The average productivity of wheat in Ethiopia was very low compared to the yield in other countries (Mekonnen et al., 2013).

The irrigation in agricultural management is a vital component to achieve the sustainable development in the world. But the value of irrigation-equipped areas as share of cultivated areas in Africa is substantially lower than the world (Valipour, 2013). Grasping the accurate knowledge about the phases of irrigation is helpful to scheduling and forecasting (Valipour et al., 2015) which may mean that these crops can be grown even in 'unsuitable' areas.

Conclusions

This study has attempted to estimate the climate change impact on rain dependent agriculture in Ethiopia by using GIS-MCE Planting Ecological Adaptability model. The result indicates that an increase in temperature and a frequent changing rainfall have negative impacts on the potential suitability of maize and wheat, especially on teff. Crops with cooler optimal thresholds (teff and wheat) are facing more adverse challenges in the future.

Hence, it was concluded that the nation and all other stakeholders should respond to climate change by formulating and implementing adaptive measures to minimize the negative effects on agriculture. Some recommended adaptation strategies are listed. Firstly, plant teff, maize and wheat to plateau and decrease the planting areas of these crops in the low altitude regions, as the suitability of these crops in low elevation has transferred into unsuitable levels. Secondly, transfer some parts of crops which are cool resistant, such as teff and wheat, into heat resistant crop, e.g. maize.

Conflict of Interests

The authors have not declared any conflict of interests.

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