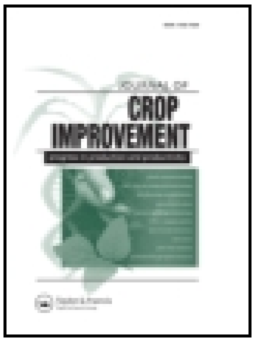

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Empirical modeling of the impact of climate change on altitudinal shift of major cereal crops in South Tigray, Northern Ethiopia

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ABSTRACT
Climate change is expected to alter the growing conditions of agricultural crops. With increasing surface temperature, future suitable areas for crop production will see an altitude shift. Such shift is an adaptation response of crops to climate change. However, in the study area there are a limited number of studies that have dealt with geographical shifts of crops caused by climate change. This study was conducted with the aim of assessing impacts of climate change on altitudinal migration of crops and length of growing period (LGP). The climate and crop modeling study were carried out using ArcGIS, Diva GIS and MaxEnt using 30 years of climate data for the period 1980 to 2009. Results showed that wheat (*Triticum aestivum*) and barley (*Hordeum vulgare* L.) would migrate upward along the altitudinal gradients in the coming 80 years. However, areas under these crops are expected to drop by 16–100%. Highly impacted areas are expected to increase, whereas low impacted and new suitable areas are expected to decline significantly. Suitable areas for sorghum (*Sorghum bicolor*) and teff (*Eragrostis tef* Zucc.) production are expected to increase. While wheat and barley are projected to be highly affected by future climate change, sorghum and teff should be relatively stable. No significant difference was observed in LGP between the considered RCP 2.6 and RCP 8.5 climate scenarios. Therefore, this study concluded that upward movement of crops was one mechanism to adapt to climate change, and new varieties resilient to future climate change needs to be developed.

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Climate change; crop migration; environmental variables; representative concentration pathways; cereal crops

1. Introduction

Global warming is now a reality, and will continue to be so for the foreseeable future (Yao et al. 2011). Climate modeling predicts that future changes

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in climatic conditions will cause progressive yield decline in major crops in many parts of the world (Schlenker and Lobell 2010). Agriculture is both a victim and an abettor of climate change (Kang and Banga 2013). Climate change is already impacting all agricultural sectors by reducing production capabilities as well as by increasing production risks (Shiferaw et al. 2015). Crop production is central to human survival, and production of increased quantities of food is an infinitum necessity to sustain current and future global populations. Most of the developing countries are highly vulnerable to climate change because of their specific geographies, relatively large populations, and the predominant role that agriculture plays in their food security, growth, and employment generation (Banga and Kang 2014; Shiferaw et al., 2015). The adverse effects will be more profound in developing countries, such as Ethiopia, with limited adaptive capacity, than in developed countries. Significant decline in crop yields could threaten both local livelihoods and the food supply systems of many countries, highlighting the need for effective adaptation measures to keep farmers employed and fields productive (Nelson and Finan 2009). The adoption of crops and crop varieties that are suited to new climatic conditions has been suggested as one possible adaptation strategy (Ortiz 2011).

Wheat (*Triticum aestivum*), barley (*Hordeum vulgare* L.), teff (*Eragrostis tef* Zucc.) and sorghum (*Sorghum bicolor*) are among the major cereal crops that supply the bulk of the staples for the population in Southern Tigray. However, the yields of cereals have been below 2.5 t ha^{-1}, resulting in food insecurity. Often highland crops, such as wheat and barley, are susceptible to the effect of climate change and even a slight change in climate affects production of the major crops significantly (Chen, Chen, and Xu 2016).

Since 2012, with the aim of doubling crop production, “Capacity development for scaling up of evidence-based best practices for increased agricultural production in Ethiopia” (CASCAPE for short), has been testing, validating and disseminating high-yielding and disease-resistant varieties of cereal crops in Southern Tigray. Improved varieties, which have proven to be productive, were screened and promoted for up-scaling through a regular extension system organized under the Bureau of Agriculture and Rural Development of the region.

A substantial body of literature shows that global warming has already induced latitudinal and altitudinal changes in the ranges of many wild species (Skarbø and VanderMolen 2016; Parolo and Rossi 2008); yet research on corresponding shifts of agricultural crops and varieties remains scanty. A limited number of studies have shown changes in growing environment of different crops under future climate scenarios (Evangelista, Young, and Burnett 2013; Chemura, Schauberger, and Gornott 2020; Sloat et al. 2020). These studies reported that latitudinal growing ranges of crops were likely to change in decades to come. But little is known how the future climate change would affect the potential distribution and suitability of major crops along altitudinal gradient. The implication remains serious for countries like Ethiopia, which is striving to achieve food self-sufficiency by increasing the yields of wheat, barley, sorghum and teff.

Climate change amplifies rainfall variability, making it difficult to predict its onset and cessation. In Ethiopia, the onset and cessation of rainfall vary considerably within a relatively short distance because of altitudinal variations, orientation of mountain chains and their physical influence on atmospheric flow (Asfaw et al. 2018). Ethiopia's agricultural system is highly dependent on rainfall, particularly on the amount and seasonal distribution of precipitation (Tefera 2012; Bewket 2009). Both are highly erratic and difficult to predict in space and time. Ethiopia's agricultural system is already extremely vulnerable to climate, and history has repeatedly demonstrated the cascading effects of crop failure and magnitude of its consequences (Evangelista, Young, and Burnett 2013; Shiferaw et al., 2015). To plan rainfed agriculture under the current climatic conditions, dependable probability levels of onset and cessation of the rainy season and length of growing period (LGP) are important (Mugalavai et al. 2008). In Tigray, farmers start planting crops based on their experience but often face germination problems because of delayed onset of rainfall, forcing them to replant the fields. As a result, crop yields suffer significantly, with either a late onset or early cessation of the growing season, as well as with a high frequency of damaging dry spells within the growing season. The ability to effectively estimate and predict the actual start of the rainy season, therefore is vital. Furthermore, understanding the direction and magnitude of crop migration and shift along an altitudinal gradient is crucially important to design adaptation strategies that would help farmers decide on how to use the currently suitable climatic situation to maximize yield of crops. Development of decision-support tools is helpful to prioritize actionable strategies, technologies, and practices and manage trade-offs (Banga and Kang 2014). Predictions of future climates, or availability of the best information, can allow to plan and also afford the time to identify and develop the interventions and cultivars that will be appropriate for the future climate and environment (Molyneux, Soares, and Neto 2014).

Therefore, the objectives of this study were to: (1) identify the main environmental variables that determine the ecological distribution and yields of major cereal crops in southern Tigray; (2) to map out the climatically suitable areas and establish current and future climatic thresholds for selected cereal crops; (3) determine the magnitude and direction of crop migration and shift along altitudinal gradients, thereby identifying suitable areas; and (4) predict the range of dates for rainfall onset and cessation, the length of the rainy season and their variability, as influenced by climate change.

2. Materials and methods

2.1. *The study sites*

The study area covers two highland (Ofla and Endamohoni) and two lowlands (Raya Azebo and Raya Alamata) districts in Southern Tigray, where CASCAPE project was operational (Figure 1). The two highland districts represent agro-ecological zones (AEZs) for wheat and barley cultivation, whereas the two lowland districts represent AEZs for growing sorghum. Teff, on the other hand, grows in a wide range of AEZs, from lowlands of Raya Azebo and Raya Alamata to highlands of Ofla and Endamohoni. In each district, one central weather station was selected for accrual and analysis of time series climatic attributes. The study districts are described in Table 1 and Figure 1.

2.2. *Model specification and environmental variables*

MaxEnt model was used for modeling distribution of the crops because it is one of the top-performing models and its input data requirements are relatively small (Elith et al. 2006). In addition, it is less sensitive to the multicollinearity problem (Phillips, Anderson, and Schapire 2006). It showed

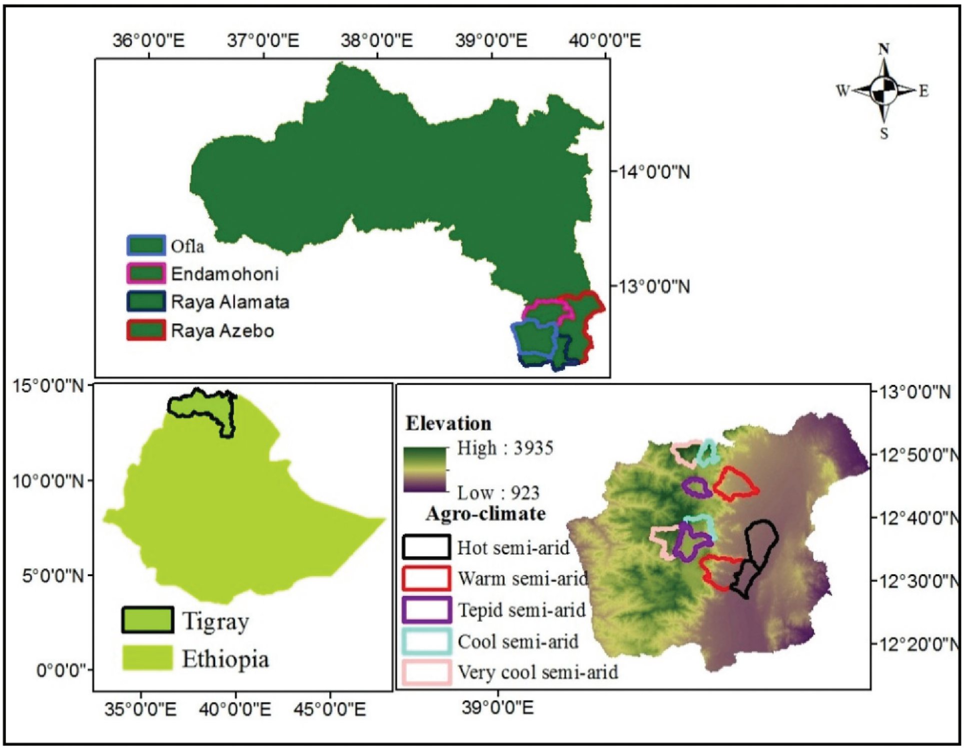

Figure 1. Map of the study area and agro-ecological zones in southern Tigray.

Table 1. Description of study districts.

District	Raya Azebo	Raya Alamata	Endamehoni	Ofla
Coordinates	12°39′ to 12°66′ N, 39° 44′ to 39° 74′ E	12°19′ to 12°73′ N, 39°29′ to 39° 33′ E	12°44′, 12°74′N 39°29′, 39°49′ E	12°34′ to 12°72′ N, 38°96′ to 39°78′ E
Altitude	930 to 2300 m.a.s.l	1179 to 3184 m.a.s.l.	1,700–3,960 m.a.s.l.	1425 to 3608 m.a.s.l
Annual temperature	15–30°C	14–26°C	9–22°C	10.4–23°C
Average annual rainfall	550 mm	668 mm	787 mm	983 mm

the best predictive capacity and was the most precise (Wang et al. 2007; Saatchi et al. 2008). The model requires occurrence points and environmental variables as inputs. Systematic random sampling was used to collect the occurrence data, as the target crops were found in different agro-climatic zones, namely hot semi-arid, warm semi-arid, tepid semi-arid, cool semi-arid and very cool semi-arid zones (Haftom et al. 2019). Data collection was done following two transect lines that stretch from 923 to 3935 meters above sea level (m.a.s.l.). One of the transact lines starts from the lowlands of Raya Azebo to the highland parts of Endamehoni and the other line passes from the lowland part of Raya Alamata to the highlands of Ofla. Two kebeles (lowest administrative units) were selected from each agro-climatic zone. A total of 124 points for sorghum and teff, and 107 occurrence points for wheat and barley production were collected from the five agro climatic classes. Geographic locations of the sampling area were recorded using a hand-held global positioning system (GPS) (Garmin 72 H). In addition, farmers were interviewed to obtain perception data on climate change and its impact on crop migration.

MaxEnt model requires environmental variables for the analysis of baseline and future distribution changes of the target crops. About 19 gridded bioclimatic variables and altitude were obtained from the world climate data set (http://www.worldclim.org/version1.4). Environmental variables with a spatial resolution of one square km were used. WorldClim is a baseline climate model that calculates current and future climate conditions at a 1 km^2 resolution (Molyneux, Soares, and Neto 2014) and it is produced based on information collected from tens of thousands of weather stations around the world (Hijmans et al. 2005). Newly developed representative concentration pathways (RCPs) under three ensemble General Circulation Model (GCM) were used to explore the impacts of future climate change on altitudinal shift and response of crops.

Ensemble GCM method was used to reduce model uncertainty caused by the structural dissimilarities among GCMs (Semenov and Stratonovitch 2010). The GCMs selected for the study were ACCESS1-0, Community Climate System Model version-4 (CCSM4) and Model for Interdisciplinary Research on Climate (MIROC5). These GCMs were selected on the basis of the consistency of their outputs among regions and wide use in sub-Saharan Africa. RCP2.6 and RCP8.5 were selected to show the trend on the two extremes representing low and high emission scenario, respectively. This is then useful to set valuable recommendations, expecting the highest and the lowest emission scenarios. RCP2.6 is known as lowest emission scenario (Van Vuuren et al. 2011; Thomson et al. 2011). RCP8.5 is a scenario of comparatively high greenhouse gas emissions and is the upper bound of the RCPs (Riahi et al. 2011). RCP8.5 corresponds to a high greenhouse gas emissions pathway (Fisher et al. 2007), and is a so-called baseline scenario that does not include any specific climate mitigation target (Riahi et al. 2011). The environmental variables were extracted down to the Ethiopia-Tigray-Southern zone map extension to predict shifts of growing condition and response of crops for the baseline (1950–2000), middle (2040–2060), and end (2060–2080) of the 21st century. The environmental variables used in the study are listed in Table 2.

2.2.1. *Environmental contribution*

MaxEnt's jackknife test and percent contribution table of variables were used to rank the most importance variables. For this, quantitative contributions of the major climatic factors to the distribution of the crops were generated using the Jackknife procedure in the MaxEnt model.

2.2.2. *Evaluating model performance*

Model performance was determined by means of Receiver Operating Characteristic (ROC) plots (Bourou et al. 2012). The area under ROC curve is generally used to evaluate the simulation accuracy of the model . The ROC plot was developed by dividing the occurrence data into two parts. In this study, 80% of the observed crop data (training data) were used to construct the MaxEnt model, which is then used to obtain the model parameters and the remainder 20% of the data (test data) were used to evaluate the applicability of the constructed MaxEnt model.

The area below the ROC curve, i.e., the value of the area under the curve (AUC), indicates the predictive accuracy of the model. The value of AUC ranges from 0.5 and 1, indicating the following degrees of predictive

Table 2. Environmental variables used in the model.

Code	Bioclimatic variables
Bio1	Annual Mean Temperature
Bio2	Mean Diurnal Range [Mean of monthly (max temp – min temp)]
Bio3	Iso thermality [(Bio02/Bio07)×100]
Bio4	Temperature Seasonality [standard deviation ×100]
Bio5	Max Temperature of Warmest Month
Bio6	Min Temperature of Coldest Month
Bio7	Temperature Annual Range [Bio05-Bio06]
Bio8	Mean Temperature of Wettest Quarter
Bio9	Mean Temperature of Driest Quarter
Bio10	Mean Temperature of Warmest Quarter
Bio11	Mean Temperature of Coldest Quarter
Bio12	Annual Precipitation
Bio13	Precipitation of Wettest Month
Bio14	Precipitation of Driest Month
Bio15	Precipitation Seasonality [Coefficient of Variation]
Bio16	Precipitation of Wettest Quarter
Bio17	Precipitation of Driest Quarter
Bio18	Precipitation of Warmest Quarter
Bio19	Precipitation of Coldest Quarter
Altitude	Altitude

accuracy: 0.50–0.60 (fail), 0.60–0.70 (poor), 0.70–0.80 (fair), 0.80–0.90 (good), and 0.90–1.0 (excellent). A model with a large area under the ROC curve indicates that the model is able to accurately predict presence and absence of the crops.

After applying a threshold, model performance was investigated using the extrinsic omission rate, which is the fraction of the test localities that fall into pixels not predicted as suitable for the crop, and the proportional predicted area, which is the fraction of all the pixels that are predicted as suitable for the crop. A low omission rate is a necessary (but not sufficient) condition for a good model (Anderson 2003).

2.2.3. *Suitability threshold estimation*

The climatic zones were classified according to their suitability for wheat, barley, teff and sorghum cultivation in Southern Tigray based on the probability (p) of existence derived from the MaxEnt model. The probability from the MaxEnt model ranges from 0 to 1. This concept assumes that sites with a probability of $0 \leq p < 0.166$ are unsuitable, $0.166 \leq p < 0.333$ are less suitable, $0.333 \leq p < 0.499$ are suitable, $0.499 \leq p < 0.665$ are optimally suitable and $p \geq 0.665$ are highly suitable for wheat and barley, whereas sites with a probability of $0 \leq p < 0.1616$, $0.1616 \leq p < 0.3231$, $0.3231 \leq p < 0.4847$, $0.4847 \leq p < 0.6462$ and $p \geq 0.6462$ were considered unsuitable, less suitable, suitable, optimally suitable and highly suitable, respectively, for sorghum and teff production. These thresholds were produced on the basis of the crops' current distribution in relation to the environmental variables. To make a clear distinction among the suitability thresholds, they were categorized as follows: unsuitable to less suitable ($p < 0.33$), suitable to optimally suitable ($0.33 < p < 0.665$) and highly suitable ($p > 0.665$).

2.2.4. *Modeling the impact of climate change on crop distribution*

MaxEnt generates binary presence (1) and absence (0) raster of potential distribution areas. Binary raster of current and future potential distribution areas was used to identify the impact of climate change on the distribution of the species. Overlying binary rasters in global information system (GIS) environment results in four possible situations for each cell (Table 3). Subtracting the current potential under each situation from the future potential of the same situation gives the potential area available for crop production. DIVA-GIS software was used to evaluate the impact of climate change on the distribution of the studied crops.

2.3. *Analysis of onset, cessation and length of growing period*

Onset is determined using a method described by Stern et al. (1982) that considers at least 20 mm rainfall accumulated across three consecutive days.

Table 3. Overlaying maps of current and future potential areas.

Situation	Definition	Future potential area	Current potential area	Results after subtracting potential areas
High impact areas	Areas where a crop potentially occurs in the present climate but which will not be suitable anymore in the future.	0	1	−1
Outside of realized niche	Areas that are neither suitable under current conditions nor under future conditions.	0	0	0
Low impact areas	Areas where the crops can potentially occur in both present and future climates.	1	1	0
New suitable areas	Areas where crops could potentially occur in the future, but which are not suitable for natural occurrence under current conditions.	1	0	1

It is not considered onset if 9 days of dry spell happened in the next 21 days. The long-term monthly rainfall distribution for the study area was obtained from the weather stations available in the study area and managed by the National Meteorological Agency. June 1 was taken as the earliest possible onset of the rains during the main rainy season (June–September). Accordingly, the potential starting date of the growing season was defined as the first rainfall event from June 1 that had at least 20 mm rainfall within a 3-day period.

The end of the rainy season was determined from the rainfall and evapotranspiration relationship. The end of the season is known when half evapotranspiration exceeds the rainfall plus the time required to obtain an evapotranspiration of 100 mm of water stored in the soil (Stern et al. 1982). The rainy season was assumed to end on 1st September when 5-day cumulative rainfall was less than 0.5 mm of the evapotranspiration. During the rainy season, the evapotranspiration was estimated to be 4.5, 5, 5.3, and 5.6 mm day^{-1} in cool, tepid, warm and hot agro-climatic zones, respectively. Hence, the end of the growing season was extended by 22 days (100 mm/4.5), 20 days (100 mm/5), 19 days (100 mm/5.3), and 18 days (100 mm/5.6) in cool, tepid, warm and hot agro-climatic zones, respectively.

Length of the growing period (LGP) is a determinant factor in deciding on the type of crops and cultivars to be grown in different rainfall regimes (NMA (National Meteorology Agency) 1996). Therefore, LGP is the period from the start of the rainy season to the cessation of the rainy season. It can be easily computed by subtracting the onset date from the cessation date (Mupangwa, Walker, and Twomlow 2011).

3. Results

3.1. *Model performance*

MaxEnt had reasonably high AUC values, indicating strong performances (Table 4). Accordingly, the model performance is rated as excellent as AUC ≈ 1 (Table 4). The performance of the models was plotted as shown in Figure 2.

3.2. *Important environmental variables*

The results of jackknife analysis showed that precipitation of the driest quarter (46.4%) and precipitation of the warmest quarter (32.1%) explained 78.5% of distribution of sorghum and teff production area. Other environmental variables, such as maximum temperature of the warmest month (5.2%), altitude (4.1%), precipitation of the driest month (4%), and temperature seasonality (2.9%), all together contributed only 16.2% toward the distribution of sorghum and teff production area (Figure 3a).

Similarly, precipitation of the warmest quarter alone explained 82.2% of distribution of barley and wheat cultivation. Precipitation of the driest quarter (4.4%), mean temperature of the wettest quarter (4.2%), iso-thermality (3.5%), temperature seasonality (1.2%), annual mean temperature

Table 4. Model performance.

Crop type	AUC[†]	Training omission rate	Test omission rate	P-value	Performance
Barley and wheat	0.992 ± 0.002	0.078	0.000	0.0018	Excellent
Sorghum and teff	0.987 ± 0.001	0.077	0.077	0.000	Excellent

†Area under the curve.

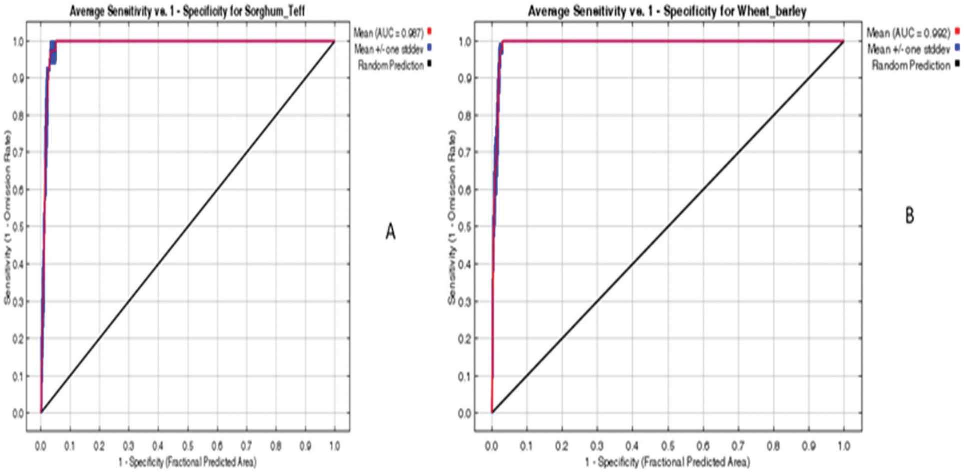

Figure 2. Model performance (A = Sorghum and Teff; B = Wheat and Barley).

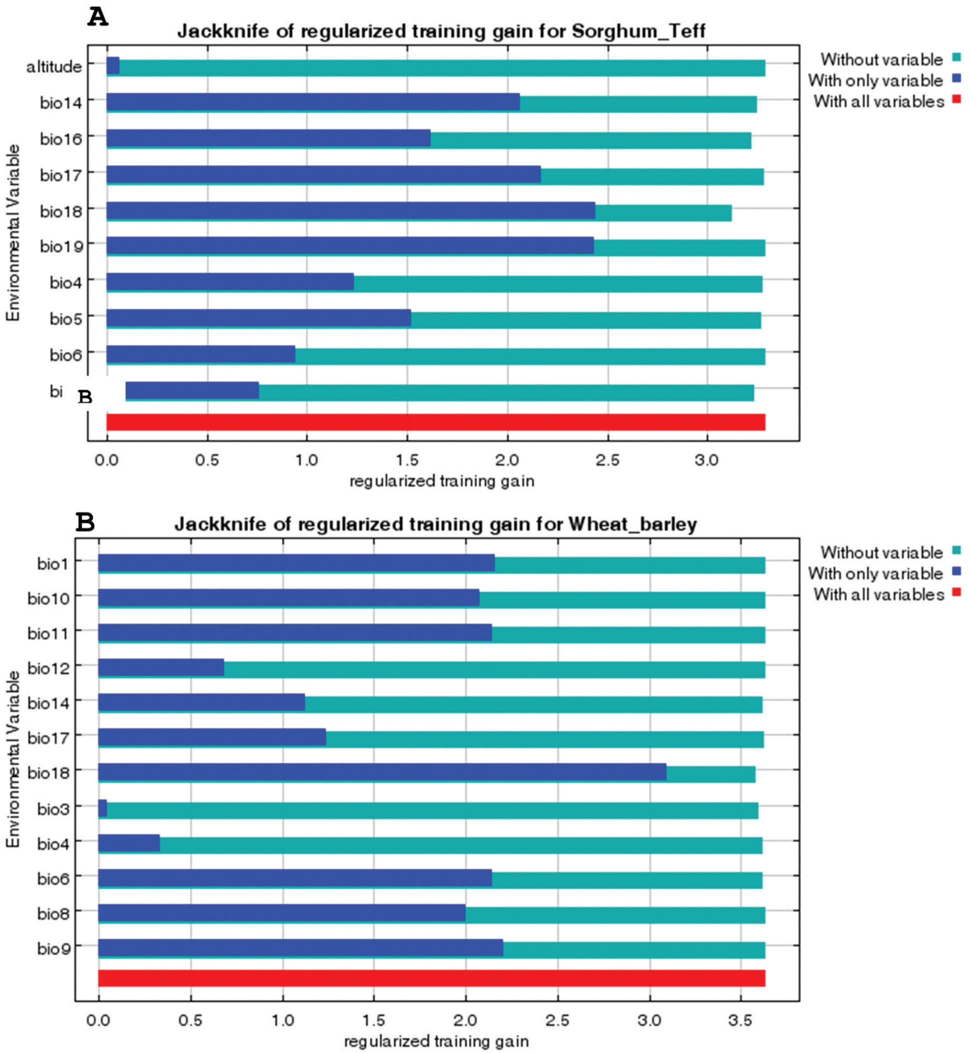

Figure 3. Contribution ratio of potential climatic factors indicating their influence to distribution of A) Teff-wheat, and B) Barley and sorghum cultivation.

(1.1%), and mean temperature of the driest quarter (1.1%) explained distribution of barley and wheat cultivation (Figure 3b).

3.3. *Altitudinal migration of the crops*

By 2050 and 2070, cultivation of wheat and barley would be expected to shift to higher altitudes, with relatively higher rainfall compared with their current environmental conditions. The effect was more pronounced on the lower altitudinal limit, within which the crops are currently growing. On the other hand, suitable areas for sorghum and teff production under future climatic scenario showed a shift to lower and higher altitude with low and higher

Table 5. Environmental conditions suitable for wheat and barley production under different climatic scenarios at different periods.

Scenarios	Rainfall	Altitudinal range (Average)	Average temperature	Minimum temperature	Maximum temperature
Current	673–924	2012–3773 (2893)	8.1–18.5	−2.2–7.2	18.4–31.2
2050 RCP2.6	732–979	2048–3773 (2911)	9.1–17.8	0.2–7.9	20.8–31.7
2050 RCP8.5	823–1038	2445–3654 (3050)	11.3–18.3	1.2–7.0	21.4–30.2
2070 RCP2.6	802–1038	2343–3773 (3058)	9.3–18.2	−0.7–7	19.3–30.6

Table 6. Environmental conditions suitable for teff and sorghum production under different climatic scenarios (figure in parenthesis indicates the average of the ranges).

Scenarios	Rainfall	Altitudinal range (Average)	Average temperature	Minimum temperature	Maximum temperature
Current	582–835	994–2402 (1698)	20.6–24.8	9.5–14.5	33.1–36.9
2050-RCP 2.6	541–894	966–2474 (1720)	19.4–25.4	9.7–16.6	33.3–38.3
2050-RCP 8.5	552–895	966–2406 (1686)	22.6–27.6	11.8–17.5	34.9–39.0
2070-RCP 2.6	580–919	994–2203 (1599)	22.4–26.5	11.6–16.3	34.7–37.8
2070-RCP 8.5	566–878	994–2406 (1700)	23.1–28.0	12.1–17.8	35.4–39.8

rainfall, respectively. But the shift is generally low and stable. Table 5 contains environmental conditions for wheat and barley under different climatic scenarios. Detailed requirements of teff and sorghum crops in different time series and scenarios are presented in Table 6.

3.4. *Potential current and future distribution of wheat, barley, teff and sorghum cultivation*

3.4.1. *Wheat and barley cultivation*

The climatic zones of Southern Tigray were classified according to their suitability for crop cultivation based on the existence probability derived from the MaxEnt model. The MaxEnt model indicated that areas that were unsuitable or less suitable for wheat and barley cultivation would increase, whereas areas that were suitable to optimum suitable and suitable to highly suitable would be expected to decrease.

The current suitable to highly suitable area for wheat and barley cultivation is 16% and this is projected to be 14%, 4%, 5%, and 0% under 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climatic scenarios, respectively (Table 7). This means suitable area for wheat and barley production is going to be reduced by 16%, 78%, 69%, and 100% under 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climate scenarios, respectively (Table 7).

Table 7. Suitability areas (ha) for wheat and barley cultivation under different suitability classes and climate scenarios.

Probability classes	Current	2050 RCP2.6	2050 RCP8.5	2070 RCP2.6	2070 RCP8.5
Unsuitable to less suitable (0–0.33)	4966	5116	5722	5638	5939
Suitable to optimum Suitable (0.33–0.66)	931	813	217	301	0
High suitable (0.66–1)	42	9	0	0	0

3.4.2. *Teff and sorghum cultivation*

In contrast to wheat and barley, parts of the currently unsuitable to less suitable areas are expected to become suitable for sorghum and teff cultivation under future climate scenario (Table 8). On the other hand, suitable to optimally suitable area for teff and sorghum is expected to decrease, whereas highly suitable area for the crops is expected to increase relative to the current situation.

3.4.3. *Analysis of onset, cessation and length of growing period*

Results of the analysis of long-term rainfall data indicate that growing season in hot semi-arid areas starts on July 12, in warm and tepid semi-arid areas on July 18 and in cool and very cool agroclimatic zones on July 19. These dates correspond to 194th, 200th, and 201th day of the year (DOY) for the respective agro-climatic zones mentioned above. This indicates that the growing season in hot semi-arid areas starts six to seven days earlier as compared to the other agro-climatic zones.

The start of the rainy season in hot semi-arid, warm semi-arid, tepid semi-arid, and cool/very cool semi-arid varied from June 26th (178 DOY) to August 15th (228 DOY), July 1st (183 DOY) to August 21th (234 DOY), June 26th (178 DOY) to August 28th (241 DOY) and July 1st (183 DOY) to August 25th (238 DOY), respectively. With a standard deviation (SD) of 15, 13, 14 and 12 days in hot, warm, tepid and cool/very cool semi-arid ACZs, respectively, the starting of growing season has very low standard deviation, indicating that the start of the rainy season for the summer season is stable.

The end date of the season falls on September 22nd, 18th, 23rd and 21st for the hot, warm, tepid and cool/very cool semi-arid ACZ, respectively, with all zones having coefficient of variation of <5%. The end dates of the season correspond to 266th, 261th, 267th and 265th DOY for the hot, warm, tepid and

Table 8. Suitability areas (ha) for sorghum and teff under different suitability classes and climate projection scenarios.

Probability classes	Current	2050 RCP2.6	2050 RCP8.5	2070 RCP2.6	2070 RCP8.5
Unsuitable to less suitable (0–0.3231)	4417	3334	3598	4282	3786
Suitable to optimum suitable (0.3231–0.6462)	1345	643	766	1284	124
Highly suitable (0.6462–1)	152	1937	1550	348	2004

cool/very cool semi-arid ACZ, respectively. The results indicate that the season comes to an end early in the warm semi-arid climate.

The starting and ending dates of rainy season have an effect on the length of the growing period in the main rainy season. Length of the growing period ranges from 52 to 96, 35 to 88, 47 to 97, and 49 to 93 days for the hot, warm, tepid and cool/very cool semi-arid ACZ, respectively, with a corresponding coefficient of variation of 30%, 43%, 34%, and 31%. The result further indicates the presence of high variability in the length of the growing period and this could be an indicator of the influence of climate change on crop production. Such information can be used for proper planning to improve water-use efficiency, rainwater harvesting, selection of crops and varieties and use of soil-moisture-conserving tillage practices.

According to the farmers in the study area, for the past 30 years, onset happened from early June to mid-July, which varied with agro-climatic zones. Farmers are challenged by the shifting of the onset of rainfall from June to July. Currently, the sowing of crops is 9–25 days later than it used to be 30 years ago. This has forced farmers to prefer fast-growing and drought-tolerant crops to adapt to the variability in onset of the rainy season. Comparing the current climatic conditions with that of mid- and end-term (2040–2099), the onset, cessation dates and LGP did not, however, show significant variation under the RCP 8.5 scenario in all agro-climatic zones. LGPs are more or less consistent across the time zones. However, across years variability of LGP in all agro-climatic zones is high. The results showed that high across years variability of LGP would occur in the mid- and end-term (2040–2099) of climate scenarios. This might give some indication that early-maturing crops and varieties could be dominant crops in the future, including in the cool and very cool agro-climatic zones (Table 9). Sivakumar (1988) reported that rainfed-agriculture production was highly susceptible to the across years variability of onset dates, cessation dates, and length of growing period.

4. Discussion

4.1. *Applicability of the model*

Based on the results of AUC and omission rate test of the test crops, the applicability of the model was rated as excellent. The MaxEnt model showed 99.2% predictive accuracy for wheat and barley, and 98.7% for sorghum and teff (Table 4). According to Young, Carter, and Evangelista (2011) and Dowling (2015), an AUC value of 0.5 indicates that the performance of the model is not better than random, whereas a value closer to 1.0 suggests the model is valid. The AUC of the constructed model based on the potential climatic factors affecting the distribution of the crop cultivation area was >98%. This value indicated that the constructed model had “good” predictive

Table 9. Onset, cessation and length of growing period (LGP) of current, mid-term and end-term in all agro-ecological zones (ACZs).

ACZ		Current	Mid-term	End-term	Significance
Hot semi-arid	Onset	194 (±15)	196 (±11)	196 (±11)	ns†
	Cessation	266 (±10)	269 (±11)	272 (±12)	ns
	LGP	70 (±21)	71 (±21)	74 (±22)	ns
Warm semi-arid	Onset	200 (±13)	200 (±13)	200 (±12)	ns
	Cessation	261 (±11)	263 (±12)	266 (±13)	ns
	LGP	56 (±24)	59 (±25)	62 (±26)	ns
Tepid semi-arid	Onset	200 (±14)	200 (±14)	200 (±14)	ns
	Cessation	267 (±12)	270 (±13)	274(±14)	ns
	LGP	65 (±23)	69 (±24)	72 (±25)	ns
Cool/V. cool, semi-arid	Onset	201(±12)	200 (±12)	200 (±12)	ns
	Cessation	265 (±12)	270 (±13)	273 (±15)	ns
	LGP	63(±20)	68 (±21)	71(±22)	ns

†ns = not significant at $p < 0.05$ level.

accuracy, implying that the model was suitable for predicting the geographic distribution of the target crops in Southern Tigray.

4.2. *Major climatic factors affecting the geographic distribution of teff, wheat, barley and sorghum cultivation*

The contribution of the six factors that explained distribution of sorghum and teff cultivation (precipitation of the driest quarter, precipitation of the warmest quarter, maximum temperature of the warmest month, altitude, precipitation of the driest month and temperature seasonality) was approximately 94.7%. The results show that there is variation in the importance and the threshold of the major environmental factors affecting distribution of sorghum and teff. Among the six climatic factors, precipitation of the driest quarter and precipitation of the warmest quarter explained 80% of geographic distribution of sorghum and teff.

Precipitation of the warmest quarter, precipitation of the driest quarter, mean temperature of the wettest quarter, iso-thermality, temperature seasonality, annual mean temperature and mean temperature of the driest quarter explained 97.7% of the variation in distribution of barley and wheat crops in the study area. Unlike teff and sorghum, precipitation of the warmest quarter is the most important climatic factor that controls more than 85% of wheat and barley distribution. The importance of bioclimatic variables under the climate-change scenarios indicated that thermal tolerance was more limiting of crop distribution than humidity. In addition, distribution of crops was largely determined by bioclimatic variables rather than other unexplained variables. Moreover, the results of this study indicate that there are variations in the importance and the thresholds of the major climatic factors affecting the target crops. These findings suggest that MaxEnt model can be used to classify climatic zones of the study area according to their suitability for cultivation, considering current and future climate changes.

4.3. *Altitudinal migration of crops*

4.3.1. *Wheat and barley*

The model output in this study predicts that under 2050-RCP 2.6, 2050-RCP 8.5, and 2070-RCP 2.6 climatic scenarios, the crops are expected to grow best in an annual rainfall of 855.5 mm, 930.5 mm, and 920 mm, respectively. Also, with respect to average annual temperature, wheat and barley are expected to grow better at average temperature of 13.3, 13.5, 14.8, and 13.8°C under the current, 2050-RCP 2.6, 2050-RCP 8.5 and 2070-RCP 2.6 climate scenarios, respectively. Wheat and barley cultivation might be expanded to an average elevation of 2893, 2911, 3050 and 3058 m.a.s.l under the current, 2050-RCP 2.6, 2050-RCP 8.5, and 2070-RCP 2.6 climate scenarios, respectively. This suggests that wheat and barley would be expected to grow at higher altitudes; the biggest shift to higher-altitude production appears to be for the 2050-RCP 8.5 scenario.

4.3.2. *Teff and sorghum*

The model output shows that both crops are expected to be grown at an average annual precipitation of 717.5, 723.5, 749.5 and 722 mm under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climate scenarios, respectively. The average annual temperature requirement might increase to 22.4°C, 25.1°C, 24.45°C, and 25.5°C under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 scenarios, respectively, from the current temperature of 22.7°C (Table 6). The projected suitable area of the crops is expected to exist at lower and medium elevations (994–2474 m.a.s.l) (Table 6). Accordingly, sorghum and teff cultivation under the current, 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climate scenarios will be predominately at an average elevation of 1698, 1720, 1686, 1599 and 1700 m.a.s.l, respectively. Unlike wheat and barley, sorghum and teff production shows a relatively small shift in response to climate change. The current suitable area will remain suitable even in the future. Comparatively, sorghum and teff are stable and less sensitive to the effect of climate change, whereas wheat and barley are highly sensitive and there is a relatively higher upward altitudinal shift for these two crops in response to climate change. Similar to this study, Evangelista, Young, and Burnett (2013) reported up to 82% teff and sorghum stabilization under medium and high greenhouse-gases emission scenarios.

4.4. *Potential current and future distribution of crops*

4.4.1. *Wheat and barley cultivation*

The suitable area for wheat and barley in the future will be reduced by 16–100%, considering the two RCPs and time slices. This implies that future climate (mid-term and end-term climate scenarios) will have higher impact on wheat and barley production compared with the current climate. Generally, the results of the climate change and crop distribution show that the major crops growing in Southern Tigray are likely to be negatively affected by future climate change. Results of this study clearly show that the crops will experience notable declines in suitable niches for wheat and barley crop production. With the expansion of unsuitable and less suitable areas for wheat and barley production, the suitable, optimum suitable, and highly suitable climatic niches will be narrowed under future climatic conditions. Figure 4a represents the current suitable area, whereas Figure 4b-e represents the predicted crop migration along altitudinal gradients as a result of climate change.

The impact of climate change is not uniform, both spatially and temporally. Results of climate impact analysis showed that future climatic conditions would have a different level of impact on wheat and barley production than the current climatic condition. For wheat and barley production, areas likely to be highly impacted by climate change are expected to increase by 3.6%, 6.3%, 6.4%, and 7.1%, whereas areas outside the realized niche are expected to increase by 91.6%, 92.7%, 92.6%, and 92.9% in 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6 and 2070-RCP 8.5 climate scenarios, respectively. On the other hand, low impacted areas will decline to 3.5%, 0.8%, 0.7%, and 0%, whereas new suitable area available in 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 will be 1.3%, 0.2%, 0.3%, and 0%, respectively. Wheat and barley are highland crops and are more sensitive to climate change than sorghum and teff. In Ethiopia, wheat is grown at altitudes of 1600 to 3200 m (Holy, Schmidt, and Schröder 2011).

Chen, Chen, and Xu (2016), based on a flexible statistical model, found negative effects of warming on wheat and barley yields in Western Europe. Climate change variables have differential impacts on yield and growth of wheat and barley. The yields of barley and wheat are decreasing because of increased temperatures and decreased precipitation (Albaba 2018). In Australia, Shabani and Kotey (2016) reported that area under wheat would decrease significantly in the future. Similarly, Tan et al. (2016) estimated that potential suitable areas in Ethiopia for wheat production would be reduced by 33% to 29% within 65 years. Similarly, Evangelista, Young, and Burnett (2013) found up to 53% reduction in suitable area for barley production for the period from 2020 to 2050 under medium and high greenhouse-gases emission scenarios.

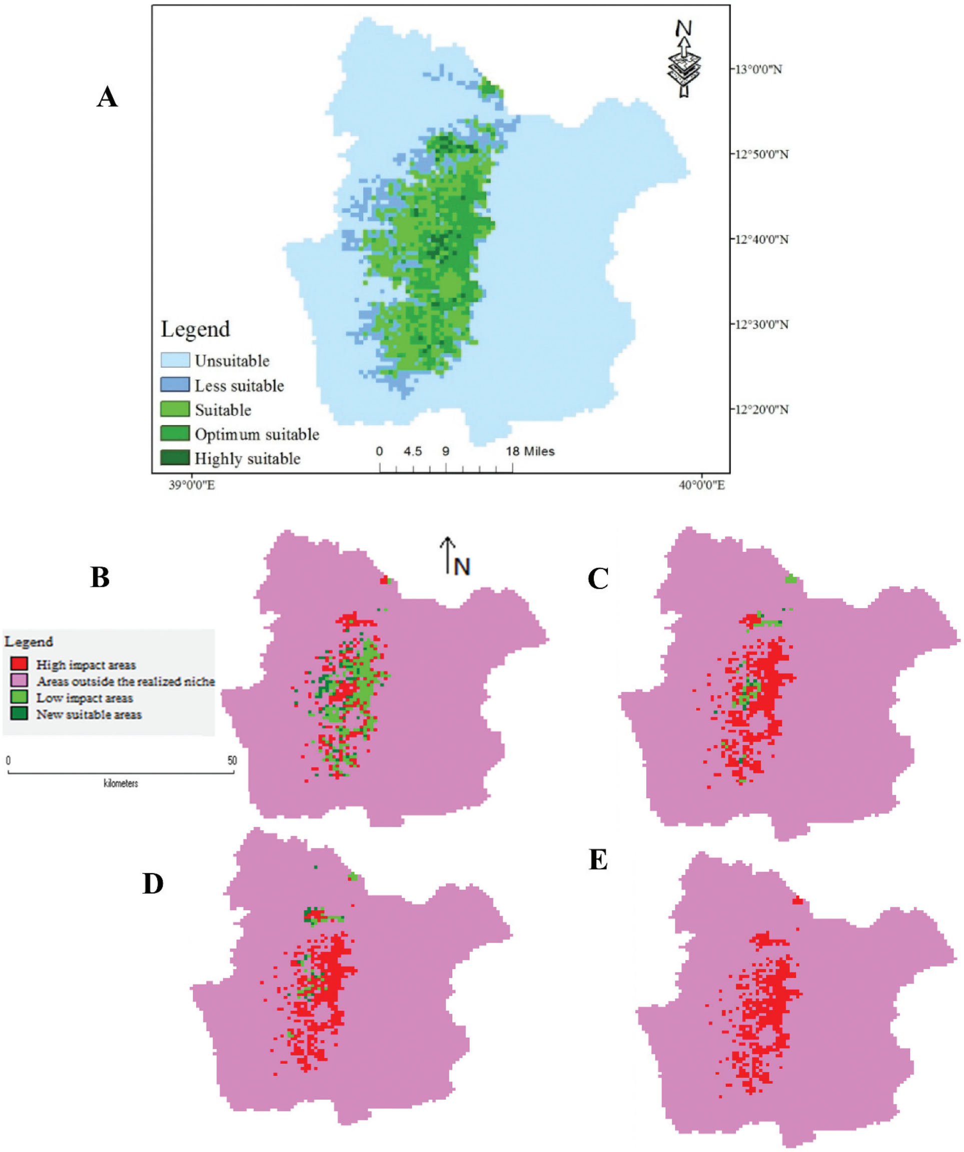

Figure 4. (a) Current suitable areas for wheat and barley cultivation; (b-e) Impact of climate change on wheat and barley suitable area under 2050-RCP 2.6 (4b), 2050-RCP 8.5 (4 C), 2070-RCP 2.6 (4D), and 2070-RCP 8.5 (4E).

4.4.2. *Teff and sorghum cultivation*

Under the current climatic conditions, teff and sorghum cover 25% of the cultivated land, but the area under these crops is projected to increase by 44%, 39%, 28%, and 36% under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climate scenarios, respectively. Areas that are currently unsuitable or less suitable are going to shift to suitable, optimum and highly suitable under future climate changes. Our results show that suitable to highly suitable area will increase by 72.5%, 54.8%, 10%, and 42.3% under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6 and 2070-RCP 8.5 climate scenarios, respectively (Table 7). Unlike wheat and barley, the expansion of teff and sorghum will be both upward and downward. Areas suitable for teff and sorghum will be higher in the mid-term climate scenario, but the magnitude will decline under higher emission rate and long-term climate change. However, expansion of teff and sorghum to lower elevations was beyond our expectation. Our assumption was that lower altitudes were already hot and the future climatic changes would make them hotter, thus, making them unsuitable for teff and sorghum production. Figure 5a represents suitable area for teff and sorghum production under the current climatic scenario, whereas Figure 5b-e represents the impact of climate change on future suitable area.

Our results clearly indicate that the distribution of the crops varies in space and time. The distribution is mainly linked to the response of these crops to climate change and it generally follows the trends of climate change. Other factors could have also contributed to the movement of the crops from one elevation to another elevation, but their contributions seem to be limited.

Scenario-prediction maps show significant changes from the current to the future predicted distribution of sorghum and teff. An area with high impact of climate change will have 0%, 0%, 2%, and 1% coverage under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8 scenarios, respectively, whereas the corresponding areas outside the realized niche will have 60%, 68%, 83%, and 64% of the total area under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 scenarios, respectively. Low impacted areas will account for 14%, 14%, 12%, and 13% under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 scenarios, respectively. Similarly, new suitable area for sorghum and teff production under the 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 climatic scenarios accounts for 26%, 19%, 3%, and 22%, respectively (Figure 5). This result corroborates the work of Reynolds et al. (2015), who reported that sorghum was often grown by subsistence farmers on marginal lands with low use of inputs. Its drought tolerance makes it an important crop for climate resilience in smallholder farming systems of Africa (Hadebe, Modi, and Mabhaudhi 2017). Teff suitability increase at altitudes between 1200 and 2500 meters (Yumbya et al. 2014). Teff's optimal growing conditions coincide with its traditional production areas: 1800–2100 m.a.s.l, average annual rainfall of 750–850 mm, and average annual temperature of 10–27°C (Ketema 1997).

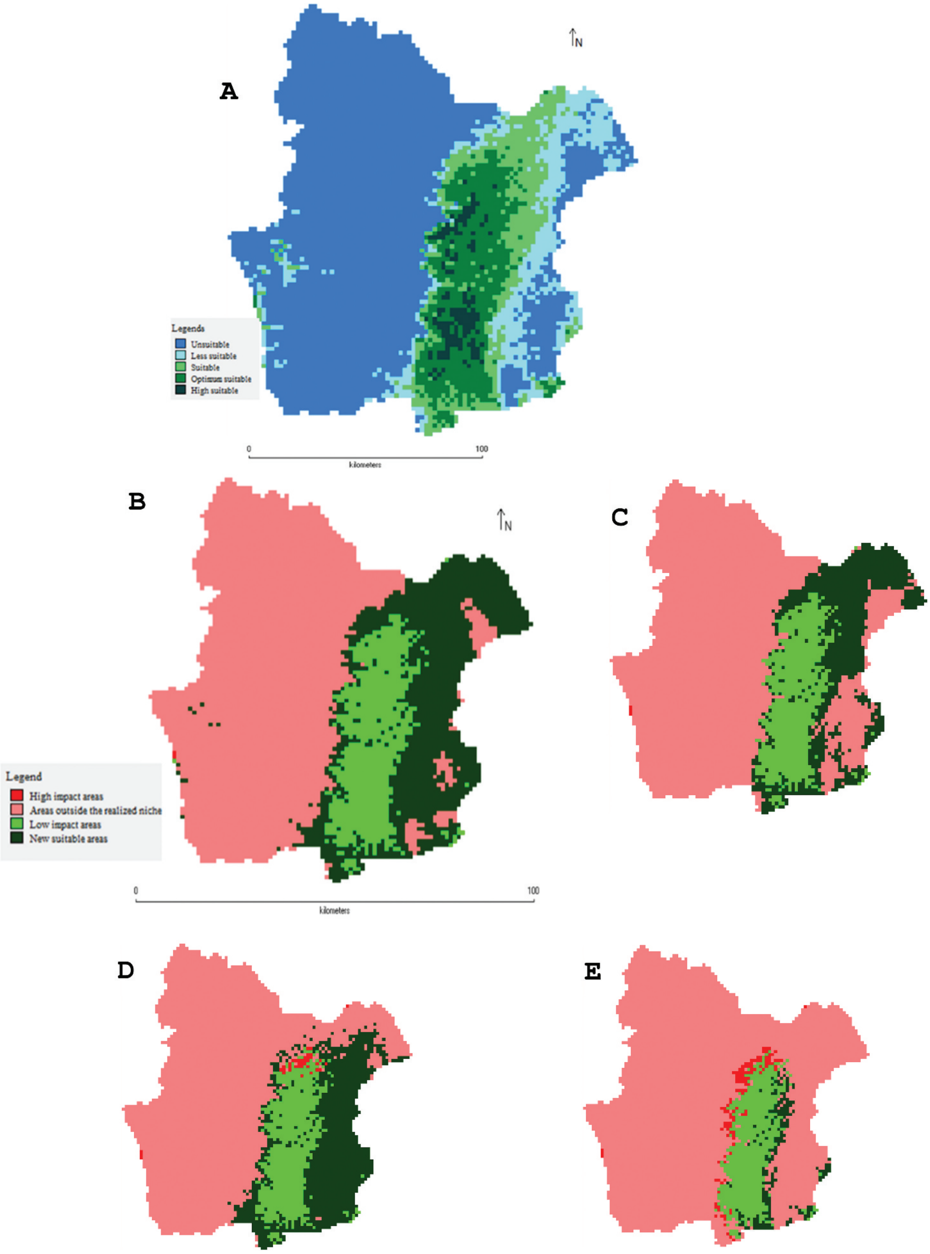

Figure 5. (a) Current suitable areas for sorghum and teff cultivation; Figure 5B, C, D, E shows impact of climate change on sorghum and teff suitability under 2050-RCP 2.6, 2050-RCP 8.5, 2070-RCP 2.6, and 2070-RCP 8.5 respectively. Red, rose, light green, dark green colors show high impact areas, areas outside the realized niche, low impact areas and new suitable areas respectively.

5. Conclusions

Because of climate change, environmental variables are changing, which will affect potential distribution of barley and wheat in the future. The general trend is toward declining areas that are suitable for barley and wheat production. Yet, future suitable climate space for wheat and barley production will be at higher elevations and will continue to shift mainly upward. Even then, with increasing climate change, suitable areas will become less suitable on account of continuing climate change. If the current scenario continues, there is high chance that production of wheat and barley will completely cease by 2070, particularly under 8.5 RCP. Comparatively, teff and sorghum are relatively stable and less affected by climate change. In future, climate change may widen suitable areas for the production of teff and sorghum both at higher and lower altitudes. As a result, distribution of teff and sorghum in the study area is expected to increase. This shows the effect of climate change varies with crop and agroecology. Future climate adaptation strategies should consider the nature of the crop, agroecology and environmental variables. Crop migration outside the current production areas is more dictated by environmental variables than by biophysical variables.

The major policy implication of this study is the need to strengthen crop breeding capacity of the country to develop climate-resilient and early-maturing varieties. This study demonstrates the need for and importance of an early-warning system that will inform research, decision-making processes, adaptive management, and development to minimize the negative impacts of climate change on food production.

It should also be noted that other than climate and altitude, distribution of wheat, barley, teff and sorghum cultivation depends on soil type, crop varieties, local production technologies, market and management. In this study, these aspects were not considered. Therefore, to assess the overall impact, these factors will need to be explored.

Disclosure of potential conflicts of interest

No potential conflict of interest was reported by the authors.

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