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GEOGRAPHIC INFORMATION SYSTEMS FOR ASSESSMENT OF CLIMATE CHANGE EFFECTS ON TEFF IN ETHIOPIA

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ABSTRACT

The value of Geographic Information Systems (GIS) for assessing climate change impacts on crop productivity cannot be over-emphasised. This study evaluated a GIS based methodology for teff (Eragrostis *tef*) production in Ethiopia. We examined the spatial implications of climate change on areas suitable for teff, and estimated the effects of altered environments on teff's productivity. There was a non-linear relationship between suitability indices, the output of spatial analysis and teff yield data collected from diverse ecological zones. This served as the basis for country-wide crop yield analysis for both current and future climate scenarios. To complement this effort, a socio-economic survey was carried with a thrust of understanding the agricultural activities in the study area. With the current climatic conditions, 87.7% of Ethiopia is suitable for teff. On the other hand, approximately 67.7% of Ethiopia is expected to be suitable for teff production by 2050. Suitability index (SI) and the actual crop yield data showed a strong positive correlation (r = 74%). There is a predicted severe drop in teff yield (-0.46 t ha^{-1}) by the year 2050. Based on the current area under teff in Ethiopia, this equals an overall reduction in national production of about 1,190,784.12 t, equivalent to a loss of US$ 651 million to farmers. The results indicate that crop yield varied significantly as a function of climatic variation and that the model is applicable in assessing the impact of climate change on crop productivity at various levels taking into consideration spatial variability of climate.

Key Words: Climate change, suitability index, teff

RÉSUMÉ

On ne saurait trop insister sur la valeur des Systèmes d'Information Géographiques (SIG) pour l'évaluation d'impacts des changements climatiques sur les rendements des cultures. Cette étude a été menée pour évaluer en utilisant le SIG la production du teff (Eragrostis *tef*) en Ethiopie. L'investigation a porté sur les implications spatiales du changement climatique sur les zones favorables à la culture du teff en Ethiopie et l'estimation des effets des changements environementaux sur la productivité du teff. L'étude a révélé une relation non linéaire entre les indices de convenance et les résultats de l'analyse spatiale et des rendements de la culture de teff dans différentes zones agro-écologiques. Ceci a servi de base à l'analyse des rendements des cultures dans tout le pays pour le présent et les futurs scenarios de changement climatique. En complément à cet effort, une enquête socioéconomique était conduite pour comprendre le déroulement des activités agricoles dans la zone d'étude. Sous les conditions climatiques actuelles, 87.7% de l'Ethiopie convient pour le teff. D'autre part, il est prédit qu'environ 67.7% de l'Ethiopie seront encore faborable à la culture du teff en 2050. L'indice de convenance et les données de rendements actuels ont montré une forte corrélation positive (r = 74%). Par ailleurs, une diminution sensible de rendement du teff (-0.46 t ha^{-1}) a été prédite pour l'an 2050. Sur base de la superficie actuelle sous culture de teff en Ethiopie, cette chute de rendement correspond à une réduction de la production nationale d'environ 1.190.784,12 t équivalents à une perte de 651 millions de dollars pour les producteurs. Ces résultats indiquent que les rendements des cultures ont varié significativement en fonction de la variation climatique et que le modèle est applicable dans le cas de l'évaluation de l'impact du changement climatique sur la productivité des cultures à différents niveaux considérant les variabilités spatiales du climat.

Mots Clés: Changement climatique, indice de convenance, teff

INTRODUCTION

The impact of rising temperatures on rainfall distribution patterns in Africa remains far less certain (IPCC, 2007). To date, it remains largely unclear what the likely extent of staple crop yield changes are and the impacts on local food security that could be anticipated given the expected changes in rainfall patterns and temperature. Several studies confirm that temperatures will rise and rainfall will increase in some places, while in others, rainfall will decrease (Rosenzweig *et al.,* 1993). However, there is general agreement among scientists that food crops are sensitive to the changing climate. Climate models predict an acceleration of recent warming in Africa, with associated changes in rainfall and the frequency of extreme events. However, studies of climate change impacts on crops in Africa show conflicting results and uncertainties, mainly relating to the methods used (Jones and Thornton, 2003; Schlenker and Lobell, 2010; Lobell *et al.,* 2011; Kelbore, 2012; Müller, 2013). A recent study using data from long term maize trials in Africa, combined with daily weather data showed a nonlinear relationship between warming and yields. Each degree day spent above 30 ^{0}C reduced the final yield by 1% under optimal rain-fed conditions (Lobell *et al.,* 2011).

Crop modelling requires detailed knowledge of many variables including climate, soil, land cover, crop requirements, water availability and on-farm management practices, which vary widely in space and time. The net effect of the variability of the factors is fluctuations and uncertainty in predicted agricultural output. In this study, we estimate suitable growing areas for teff using bioclimatic variables and teff yield data collected in the field and also generate crop yield maps for both current and future climatic conditions. We show two methodologies on use of geographical information systems (GIS) in assessing climate change impacts on the productivity of teff (Eragrostis *tef*), a major staple crop in the horn of Africa. The first method examined the spatial implications of climate change on the areas suitable for teff production. The second estimated the effects of climate change on teff production.

METHODS

The study area. The study focused on three teff growing geographic locations in Ethiopia, namely, Gimbichu, Bora (Dugda) and Minjar (Shenkora). Being in the northern hemisphere of the globe, Ethiopia generally experiences four seasons, namely: "*Kiremt*" (main rainy season, June-August), "*Tsedey*" ("spring" season, September-November), "*Bega*" (dry and sunny, December-February), and "*Belg*" (light rains, March-May). All yield data were collected during the main season. Climate variability in the country is high mainly due to the wide altitude range (Gamachu, 1988). The windward areas in the highlands receive relief rainfall, but the leeward areas and surrounding lowlands are in the rain shadow and are very arid. The districts selected for the socio-economic survey, i.e. Bora, Minjar and Gimbichu, represent three climatic zones Kolla, Weina Dega and Dega, respectively. They differ in elevation, rainfall and minimum, and maximum temperatures to a large extent determine the kind of crops grown, and potential yield.

Assessment of geographic shifts, current and potential distributions. Passport data which contained a total of 1441 geo-referenced data points, which included germplasm collections and herbarium specimens, were collected from the gene bank of the Institute of Biodiversity Conservation and the Ethiopian National Herbarium at the Addis Ababa University. Teff geographic range was modeled to determine the crop's suitable areas in Ethiopia. All base maps were obtained from DIVA GIS (www.diva-gis.org) with a reference scale of 1:10000. The methodology used in developing suitability indices is based on DIVA GIS Version 5.2 developed by Hijmans (2003).

Environmental data consisted of climate surfaces for present (1950-2010) and projected future conditions (~2050) obtained from WorldClim. For present climate, Worldclim climate surfaces (Hijmans, 2003) were used because of their high spatial resolution (1 km) and global extent. Future climate data were obtained from a number of global climate models (GCMs) with differing greenhouse gas emission scenarios, model characteristics and spatial resolutions. Data from Govindasamy *et al*. (2003) were used because they had the highest spatial resolution (50 km) based on the CCM3 model, with concentration of CO_2 in the atmosphere of 600 ppm (two times that of pre-industrial conditions).

We used Bioclim model as implemented by Busby (1991) in DIVA-GIS (www.diva-gis.org). Climate variables in the Worldclim dataset have the potential to be correlated with one another (e.g. maximum and minimum temperature). Many correlated variables can lead to statistical bias and model over-prediction. For this reason, the number of variables was minimised by selecting only those which were deemed biologically relevant to the crop. In this study, annual mean temperature, mean monthly temperatures, annual precipitation, precipitation seasonality, temperature seasonality and mean diurnal range of temperature were used.

Geographic ranges under current and future conditions for the crop were mapped in order to identify the broad spatial patterns of the impact of climate change and by what suitability index. While there are other techniques for species distribution modeling, DIVA GIS was used as it does not create response curves that may cause erratic behaviours (Hijman and Graham, 2006; Segurado and Araújo, 2004). BIOCLIM (Nix, 1986) is a commonly used modeling programme which relates climatic parameters (i.e. temperature, precipitation, moisture, etc.) to species presence data to predict areas within which an organism can survive (Beaumont *et al*., 2005). The model was run in DIVA-GIS and the output was transformed into presence/absence by assigning presence to the areas where scores were within 2.5 - 97.5 percentile range. The scores per pixel were then treated as the suitability indices.

Assessment of crop yield losses. We analysed teff yield data collected from District Offices of Agriculture and the Central Statistical Agency in Ethiopia for the 2010/11 Meher season (Table 1). Yield points were converted into shape files and overlaid on the suitability grids (from the BIOCLIM model), which had various indices. The environmental conditions where the yield points were overlaid were grouped according to the various suitability indices. Bioclimatic variables for each of the 23 yield data points were extracted from the climatic datasets using DIVA-GIS software. Each point included average minimum and maximum temperature, and average monthly precipitation. Mean annual rainfall and mean monthly temperatures were calculated from temperature and precipitation variables. This enabled the yield value to be directly correlated with the suitability index value. Two variables were extracted from the relationship, yield and suitability index. It was assumed that with all other factors held constant, the amount of yield produced by a particular crop would be approximately the same given the same climatic condition. The assumption was borrowed from Bioclim model as implemented in DIVA-GIS (Busby, 1991). The relationship between suitability index and teff yield was calculated using a simple linear regression (Equation 1). The yield and suitability index were used to predict teff yield distribution maps.

$$y = a + \mathrm{bx} \qquad \text{Equation 1}$$

Where:

a = 0.576 (intercept), b = 0.003 (slope), x = suitability index and y = yield ($t\ ha^{-1}$)

Socio-economic study. A socio-economic survey was carried out to understand the agricultural activities in the study districts, climatic changes observed, impacts of the changes as perceived by farmers, challenges faced and what farmers are doing and planning to do to mitigate negative effects of the changes in general and climate change in particular. Our sampling strategy was based on minimising the sample error and

TABLE 1. Yield in relation to suitability indices (SI), mean temperature and average rainfall

Longitude (DD)	Latitude (DD)	Yield (t ha^{-1})	Mean temperature (°C)	Average rainfall (mm)	SI value
38.5	9.0666656	1.3	15.49	202.75	198
38.716667	8.8166656	2	17.98	175	307
39.133331	9.6000004	0.925	15.39	172.75	111
40.200001	7.8499999	0.608	22.49	94	111
38.733334	14.116666	0.808	18.19	139	50
37.166664	7.5333328	0.522	16.29	217.5	79
38.200001	10.45	1.16	15.42	223.5	130
38.283333	10.5	1.16	17.46	209	199
38.133331	10.166666	1.16	15.9	210	199
38.966667	8.7333326	2.4	18.64	165.5	333
37.099998	9.5666656	0.947	14.65	312	37
37.849998	7.5500002	0.933	15.74	150.25	91
36.833332	7.666666	0.936	18.71	232.5	64
39.150002	9.8833332	1.6	15.54	176.25	160
39.416664	8.9333334	2.2	20.6	149.25	251
36.450001	11.333333	0.889	22.8	332	51
39.549999	12.416666	0.959	23.9375	97.25	56
37.700001	7.0666661	0.648	18.8125	173	72
37.483334	11.266666	0.87	16.85	296.5	93
40.783333	8.8999996	1.4	21.4	133	108
37.849998	8.9833326	1.121	16.95	179.5	291
38.200001	9.083333	1.2	15.625	198	224
38.950001	8.2833328	1	20.225	137.5	257

assuming maximum variability in the population of teff farmers. We assume a ±5% level of precision and 95% statistical confidence level.

The number of all farm holders in Ethiopia is about 12,208,970. Average cultivated land per holder is about 1.81 ha, while the average land size for cultivation of teff per holder is 0.76 ha (42.16%) of total cultivated land (CSA, 2010). The number of teff farm holders was estimated to be 5,630,440. Using the Cochran formula (Cochran, 1963) for calculating sample sizes, and assuming maximum variability (P=0.5), a 95% confidence level and ±5% precision, the sample size was calculated using Equations 2 and 3. Applying the same formula to smaller population sizes e.g. 3,289,473 or 1,380,000, resulted in the same sample size of about 400 farmers.

$$n_0 = Z^2pq \,/\, e^2 \quad \text{.................................. Equation 2}$$

Where:

n_o = the sample size; z^2 = the absisca of the normal curve that cuts off an area at the tails (1 – equals the desired confidence level, e.g., 95%); e = the desired level of precision; p = the estimated proportion of an attribute that is present in the Teff farmer population, and q = 1-p. The value for Z is derived from statistical tables which contain an area under the normal curve.

$$n_0 = \frac{(1.96)^2(0.5)(0.5)}{(0.05)^2} = 385 \text{ farmers} \quad \text{......... Equation 2.1}$$

A simplified formula for proportions is provided by Yamane (1967):

$$n = N/1 + N(e)^2 \quad \text{.......................... Equation 3}$$

Where:

N = the assumed population size, and e = the level of precision.

$$n = \frac{5,059,200}{1+5,059,200\,(0.05)2} = 400 \text{ farmers}$$

.... Equation 3

In the study, however, the general principles of this formula were followed but the sample size had to be reduced to 300 due to cost implications.

The interview approach selected for this study was that of structured interviews, though the questionnaire did contain some elements of semi-structured questions. Structured interviews have the advantage of allowing for statistical analysis of the data collected and making general comparisons. Stratified random sampling procedure was employed to select peasant associations and farmers households. From each district, ten peasant associations were randomly selected, and from each peasant association, ten farmers' households were again randomly selected. A total of 100 respondents from each of the three districts participated in the survey resulting in 300 respondents in total. The data were analysed using SPSS software.

A study was carried out to assess the extent to which climate change is likely to affect food security, socio-economic lifestyles and agricultural practices. The study was carried out using available secondary data, particularly agricultural statistics, agronomic data, policy documents and food security statistics. This information highlights the consequences of climate change scenarios on teff yields, production, and socio-economic risk. Potential impacts of climate change on teff yield were projected using a global model, which is an integrated ecological-economic modeling framework encompassing climate scenarios, agro-ecological zoning information, as well as socio-economic drivers.

The biophysical results were fed into an economic analysis to assess how climate impacts may interact with alternative development pathways, and key trends expected over this century for food demand and production. The approach connects the relevant biophysical and socio-economic variables within a unified and coherent framework to produce a national assessment of teff production and food security under climate change. Projected changes in yield were calculated using the data of area, production and yield of teff for private peasant holdings during the main (Meher) season of 2009/2010 using sample surveys compiled by the Central Statistics Agency (CSA) in 2010. Simple calculation were then used to evaluate consequent changes in national teff production and teff prices. The annual teff grain production projection estimate was calculated by reducing the total loss based on the projected estimate of 0.46 t ha^{-1} from the total current gross teff grain production. The subsequent computations were based on the statistics presented by CSA (2010).

RESULTS

Geographic shifts and impacts on yields. The model showed the species having a future climatic suitable area of a minimum annual precipitation of 600 mm and a maximum of 1900 mm. The minimum annual temperature will be 14.9 ^{0}C, while the maximum will be 26.8 ^{0}C. By 2050, 67.7% of Ethiopia land area will be suitable for the crop. High suitability index shifted from Shewa to Amhara. Areas around South Gonder, East Gojam and South Wollo were predicted to be very suitable for the species in future.

Teff will lose an average 236,976.65 km² or 24% of climatic suitable area (Fig. 2). It is predicted that the species will only be restricted in the higher altitudes. Oromia areas will lose most of its suitable area. There is a pattern of the species shifting from South-East to North-West towards the higher elevations of the Northern Ethiopia. Crop suitability areas at the lower altitudes will be affected. Suitability increased at altitudes between 1200 – 2500 meters.

The analysis of climate change effects on teff yield revealed that there is a relationship (R^2=0.74) between the suitability index (SI) and teff yield (Fig. 1). The first image in Figure 4 reveals the current prediction of teff yield using climate surfaces for present (1950-2010**)**, the 2nd image shows the predicted yield map by the year 2050 using projected future conditions. Applying Equation 1 on the predicted current suitability index grid, a drop of 0.46 t ha^{-1} was predicted in the areas marked in red (Fig. 4). Minimal increase in teff production of about 0.14 t ha^{-1} in the areas marked in blue was predicted but was negligible.

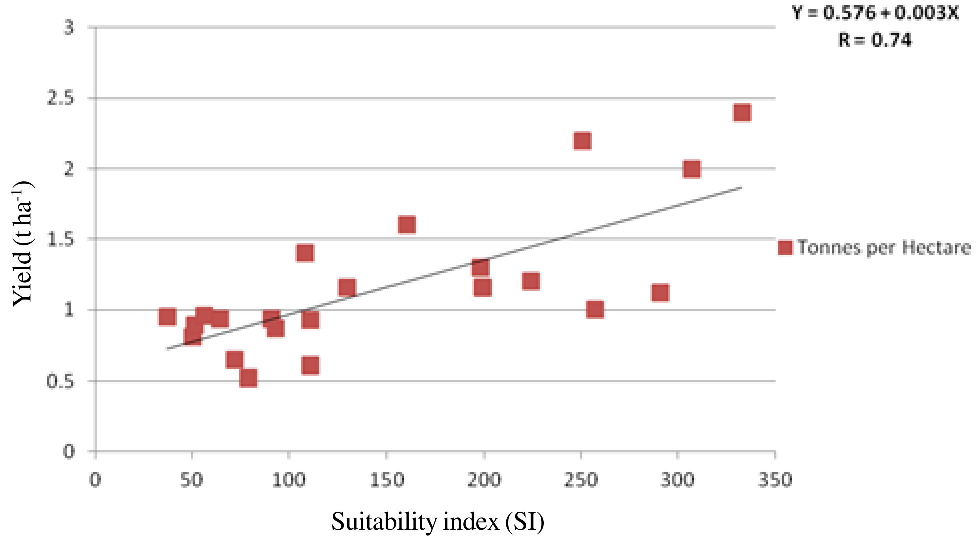

Figure 1. Scatter plot of yield versus suitability index values.

Droughts and crop production. In Bora, out of 100 respondents 43, reported reduction in teff yield. On average, over the last half decade, respondents experienced 2.5 serious droughts resulting in crop failures (Table 2). In Gimbichu only one respondent reported to have missed out on one harvest due to drought. In Minjar, out of 85 respondents, 61% reported yield reduction. Sorghum was the only cereal in Bora reported to be grown by fewer farmers than 5 to 10 years ago. There was a drop from 36 to 10% of the respondents growing sorghum. Surprisingly, despite the high risk of crop failure in maize during droughts in Bora, respondents did not shift to growing other cereals. In Minjar, there was a slight decrease in the number of respondents growing maize (from 30 to 23%), which could well be due to the high crop failure risk of maize, combined with the possibility of the shift to growing other crops. Crop failures due to drought were found to be most frequent in Bora, and least frequent (absent) in Gimbichu. Water availability seemed to have decreased as reported by 81% of the respondents. Related to rainfall is the start and length of the growing season, which according to 97% of respondents had become shorter than it was before. Temperature in general increased according to 99% of the respondents. The number of hot days in a year increased as well as the occurrence of heat waves according to 97% of the respondents.

Environmental and climatic changes. The respondents reported changes in rainfall and temperature over the last 7 years (Table 3). Bora was reportedly drier and hotter than 7 years ago (i.e. around 2003/2004). Bora experienced a decrease in the amount of rain per year (Table 3). The number of dry months in a year increased according to 98% of the respondents, though the occurrence of droughts seems to be constant.

Socio-economic implications. Based on biophysical data input in an economic analysis to project a national assessment of teff production and food security under climate change, and to evaluate consequent changes in national teff production, the model revealed large losses. Considering the current acreage and production level, the overall reduction in national production was estimated at 1,190,784.12 t. This is equivalent to an economic loss of US$ 650,961,954 to farmers using farm gate prices. At the national level, the economic loss due to teff grain yield reduction was estimated to be US$ 730, 347, 581 per year.

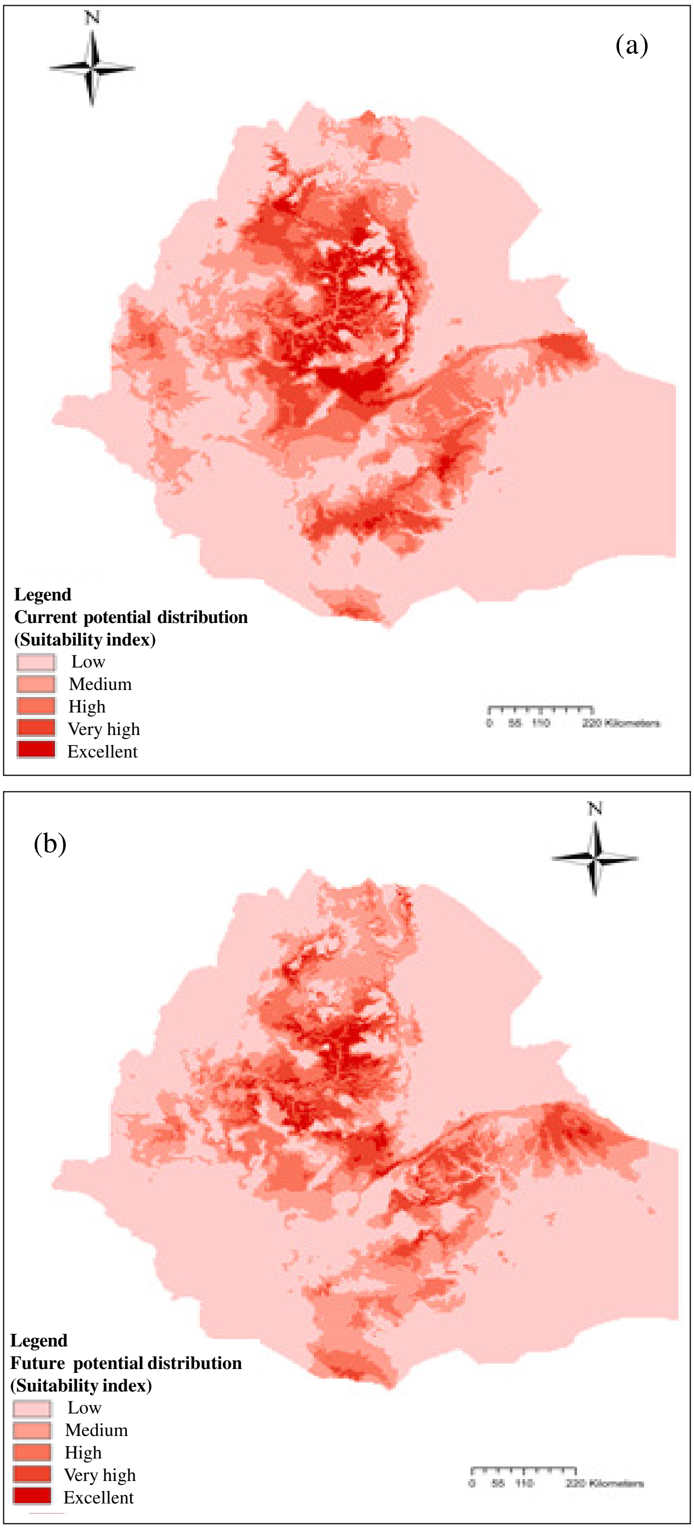

Figure 2. Predicted suitability index grids for teff in Ethiopia; current (a) with passport data overlaid and future (b). Suitability grids were calculated using climate surfaces for present (1950-2010) and projected future conditions (~2050).

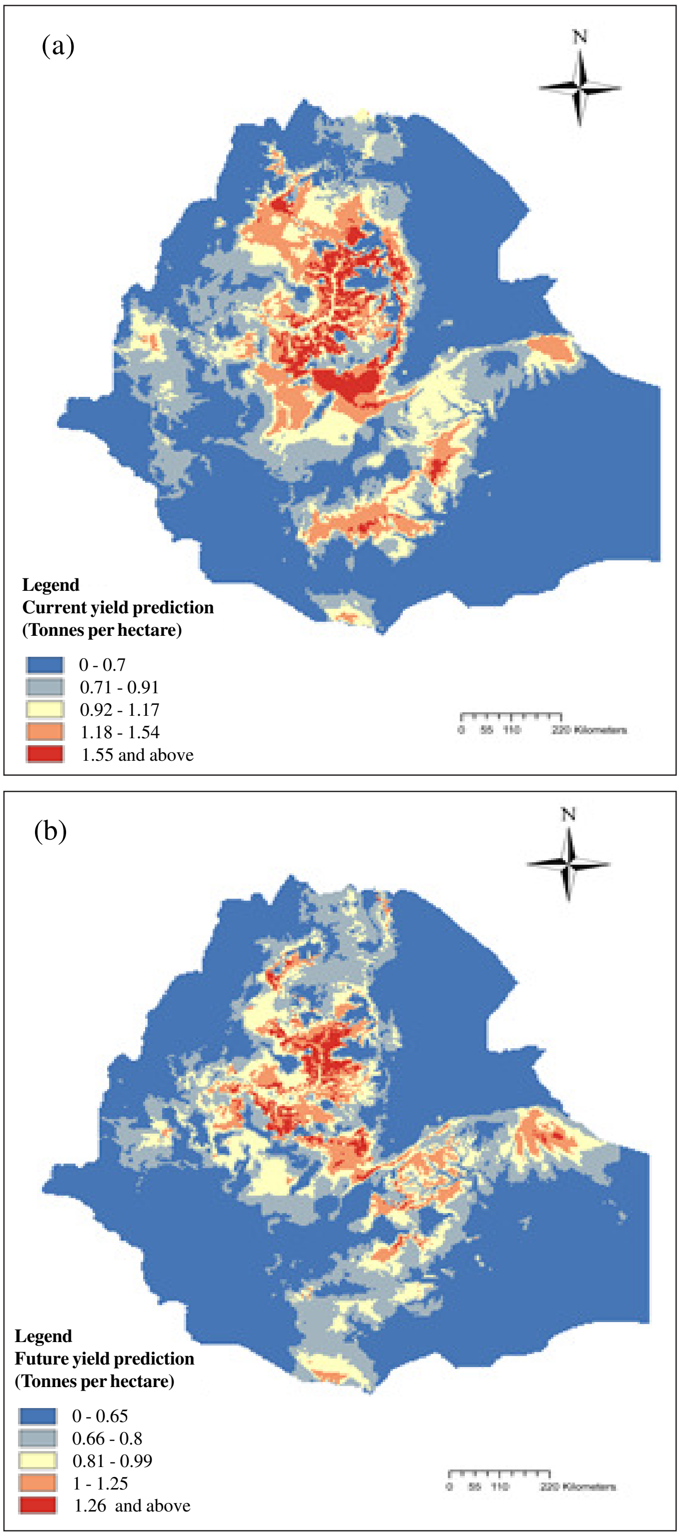

Figure 3. Current (a) and future (b) predicted teff yield distribution maps in Ethiopia. Yield was calculated by applying Equation 2 on the predicted current suitability index grid.

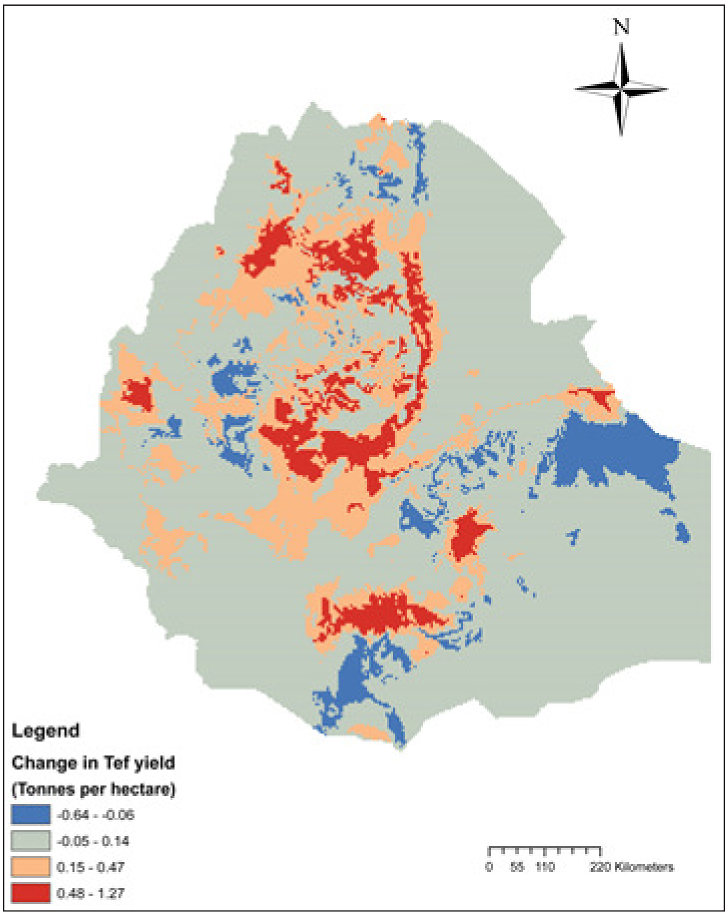

Figure 4. The predicted change in yield by the year 2050 using projected future conditions (~2050) and the current scenarios for teff in Ethiopia.

TABLE 2. Cereal crop failures due to drought in the three districts in Ethiopia over the past 5 years (2005-2010)

Site	Average number of crop failures due to drought during last 5 yrs	Specified crop failure for respondents who lost crops to droughts*				
		Teff	Barley	Wheat	Maize	Sorghum
Bora	2.5 (n=100)	43	20	68	96	22
Gimbichu	0.0 (n=1)	0	0	1	0	0
Minjar	1.4 (n=85)	61	59	89	34	31

* Frequency percentage of respondents (n)

DISCUSSION

From the study it was clear that Bora is dry and hot, with low teff yield. Strategies to improve yields have not been successful. Rainfall has decreased and is more erratic; droughts have become more common as have floods. Temperatures have increased, and there are more hot days than before. In Gimbichu and Minjar, a similar pattern of change in rainfall and

TABLE 3. Change in rainfall and temperature over the past 7 yrs (2003-2010) as perceived by respondents in the three districts in Ethiopia

Climate variables	Bora*				Gimbichu*				Minjar*			
	n	+/-	+	-	n	+/-	+	-	n	+/-	+	-
Amount of rain	100			100	99	6	35	59	100	7	13	80
Frequency of rain showers	100			100	97	4	35	61	100	10	8	82
Distribution of rainfall in the year	100			100	97	15	19	66	99	9	8	83
Number of dry months in a year	100		98	2	89	39	52	9	94	6	61	33
Occurence of droughts	100	52	25	23	73	47	14	40	78	50	22	28
Occurence of floods	100	22	68	10	76	43	36	21	81	74	5	21
Water availability	100	19		81	96	2	25	73	100	16	28	56
Water stress	100	18	81	1	95	1	49	49	98	18	34	48
Length of the growing season	100	3		97	85	28	34	36	97	14	8	77
Temperature	100		99	1	98	7	80	13	98	5	81	14
Number of hot days	100		98	2	94	14	74	12	95	6	80	14
Occurence of heat waves	100	3	97	0	75	48	41	11	83	60	30	10

* Frequency in percentage of respondents (n) i.e. +/- (no change), + (increase), - (decrease)

temperature can be seen, though far less extreme than in Bora. Climatic conditions are thought to have changed the least in Gimbichu.

The model confirmed future teff distribution changes and yields reductions due to climatic changes. There will be an average loss of approximately 24% of the current suitable area for teff by 2050. With a change in the species climatic envelope, teff will only be suitable in areas with temperatures of up to 27 °C and a low of 15 °C in 2050, but this has been compensated with increased rainfall of up to 1900 mm from a low of 600 mm. The model also predicted a complete loss of suitable areas at latitude between 6°N – 8°N and a gain at latitudes between 9°N – 11°N, but restricted to 36°E – 39.4°E longitudes.

The slight change of species distribution to Eastern Ethiopia conforms to the predicted future increase of rainfall amounts of between 1250 - 1800 mm from the current low of 950 - 1000 mm around longitude 39°E and latitude 7°N up north. The variability in rainfall intensity and duration makes the performance of agricultural systems in relation to long term climate trends very difficult to predict (Chen *et al*., 2004). A careful assessment of the predicted yield distribution maps indicates that the suitability index developed in the study correlates positively with the yield data collected in the various agro ecological zones. This means that changes in temperature, rainfall and seasonality in Ethiopia directly affect the distribution and yield of teff, a conclusion made by Kelbore (2012) and Evangelista *et al*. (2013) in previous research.

Based on predicted loss of 0.46 t ha^{-1}, the supply of teff grain will further diminish by 1,190,784.12 t from the current level of 3,179,743 t. The prices are expected to increase as the supply of teff grain decreases.

Currently the production of teff is not commensurate with the national demand for the grain. There is already a huge deficit between the production and the national demand, and this will be exacerbated by climate change effects. It is, therefore, understandable that as long as the production of teff decreases against a rising demand due to the fast growing population, there will be unprecedented price increase on teff grain. Being a major staple crop, teff is very important for national food security in Ethiopia. A threat to the crop's area suitable for cultivation due to climate change is a direct threat to food security. If teff production in Ethiopia continues to decrease with time, it will lead to a significant polarization of effects on both farm gate and market prices, with substantial increases in prices anticipated.

CONCLUSION

The methodology presented in this study provides an opportunity for agriculturalists, spatial analysts and policy makers to analyse the effect of climate change on crop productivity to inform development of adaptive strategies and policy to minimise the negative impacts of climate change on teff production in Ethiopia. Moreover, it provides opportunities for further potential research to finetune the model and communicate model predictions better. However, it would be difficult to predict the magnitude of change in production due to the fact that the reduction in teff yield is a complex pattern of climate variables, CO_2 effects, and agricultural management systems.

All these contribute to aggregations of national crop production.

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