Climate Risk Management 19 (2018) 106–119

Contents lists available at ScienceDirect

Climate Risk Management

journal homepage: www.elsevier.com/locate/crm

Potential benefits of drought and heat tolerance for adapting maize to climate change in tropical environments

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ARTICLE INFO

Keywords:
Climate change
Maize
Drought tolerance
Heat tolerance
Tropical environments

ABSTRACT

Climate change and population growth pose great challenges to the food security of the millions of people who grow maize in the already fragile agricultural systems in tropical environments. There is an urgent need for maize varieties that are both drought and heat tolerant given the already prevailing drought and heat stress levels in many tropical environments, which are set to exacerbate with climate change. In this study, the crop growth simulation model for maize (CERES-Maize) was used to quantify the impact of climate change on maize and the potential benefits of incorporating drought and heat tolerance into the commonly grown (benchmark) maize varieties at six sites in Eastern and Southern Africa and one site in South Asia. Simulation results indicate that climate change will have a negative impact on maize yield at all the sites studied but the degree of the impact varies with location, level of warming and rainfall changes. Combined hotter and drier climate change scenarios (involving increases in warming with a reduction in rainfall) resulted in greater average simulated maize yield reduction (21, 33 and 50% under 1, 2 and 4 °C warming, respectively) than hotter only climate change scenarios (11, 21 and 41%, respectively). Incorporating drought, heat and combined drought & heat tolerance into benchmark varieties increased simulated maize yield under both the baseline and future climates. The average simulated benefit from combined drought & heat tolerance was at least twice that of heat or drought tolerance and it increased with the increase in warming levels. The magnitude of the simulated benefits from drought tolerance, heat tolerance and combined drought & heat tolerance and potential acceptability of the varieties by farmers varied across sites and climate scenarios indicating the need for proper targeting of varieties where they fit best and benefit most. It is concluded that incorporating drought and heat tolerance into maize germplasm has the potential to offset predicted yield losses and sustain maize productivity under climate change in vulnerable sites.

1. Introduction

Maize is one of the most important and widely grown crops in the world. While maize is a major source of feed and industrial

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https://doi.org/10.1016/j.crm.2017.10.001
Received 9 April 2017; Received in revised form 9 October 2017; Accepted 15 October 2017

products in the developed world, it provides food, feed and nutritional security in the world's poorest regions in Africa, Asia and Latin America (Prasanna, 2011; Ranum et al., 2014). More than 73% of the maize area is found in the developing world, with a greater proportion of this area located in the low and lower middle income countries where maize provides the most food calories for millions of people (Prasanna, 2011; Shiferaw et al., 2011). The demand for maize is projected to increase in the developing world due to an increase in both food consumption and feed requirement of maize (Shiferaw et al., 2011) driven by population growth and economic development.

The average maize yields in the developing countries are still low due to abiotic, biotic and socioeconomic constraints (Shiferaw et al., 2011). In sub-Saharan Africa (SSA), maize is predominantly grown by smallholder farmers, who mostly cultivate small parcels of land, which are often degraded and have no access to reliable irrigation (AGRA, 2014). Climate change adds further challenges to the existing problems and undermines efforts that are being made to enhance food security and reduce poverty in SSA (Tesfaye et al., 2015a).

Recent climate projections indicate that temperatures over Africa will rise faster than the global average and probably exceed 2 °C by 2050 under the high emission scenario (Niang et al., 2014). Although projected rainfall change over SSA in the mid- and late- 21st century is uncertain, increased frequency and severity of extreme climatic events (severe storms, flooding, droughts, etc.) are very likely (AGRA, 2014; Niang et al., 2014). Moreover, the length of the growing period (LGP), which is an indicator of the adequacy of moisture availability and favorable temperature, is projected to decrease by 20% in most parts of SSA by 2050 (AGRA, 2014; Sarr, 2012; Thornton et al., 2011). These changes are very likely to reduce cereal crop productivity, and will have strong adverse effects on food security (Niang et al., 2014). Studies projected that climate change could decrease rainfed maize yields by more than 12% in SSA (Jones and Thornton, 2003; Tesfaye et al., 2015a) and by up to 12% in South Asia (Tesfaye et al., 2016) by 2050.

Maize grown in semi-arid tropical environments often faces a multitude of abiotic stresses such as drought and heat (Cairns et al., 2012). Drought is the most important abiotic stress factor for maize production in both the temperate and tropical environments and annual average yield losses to drought are estimated to be 15% of potential yield on a global basis (Edmeades, 2008). Additional losses of maize grain may reach 10 million tons per year as temperatures rise and rainfall patterns change under climate change (Edmeades, 2008). Moreover, major maize producing areas will become warmer, drier and subject to an array of new maize diseases and pests under climate change (Edmeades, 2013). While drought has been destabilizing maize yield in many parts of predominantly rainfed SSA, heat stress is becoming more important as the climate changes (Edmeades, 2013). Projected temperature increases will be higher in the drought-prone areas (Niang et al., 2014) indicating that drought stressed areas will also face severe heat stress under the future climate. Therefore, heat stress both alone and in combination with drought stress is likely to become an increasing challenge to maize production in SSA (Cairns et al., 2013a).

Historically crop genetic improvement has led to significant gains in productivity and offset projected losses (Evenson and Gollin, 2003). However, breeding represents a long term investment, in terms of both time and money. Although recent advances in tropical maize breeding have reduced the time taken to develop new varieties, it still requires a minimum of six years (Masuka et al., 2017a,b). Furthermore extensive resources are required for both genotyping and multi-location phenotyping (Cooper et al., 2014). Recent studies indicated that genetic gain across traits, such as drought, low nitrogen stress and diseases, was partly related to the investment in phenotyping capacity (Masuka et al., 2017a). Information on future climates require breeding programs to shift targets (Cairns et al., 2013b). Maize breeders and physiologists are already targeting specific plant traits to breed new crop varieties that will perform better under climate change (Cairns et al., 2013b). It is, therefore, important to make an early assessment of the potential benefits of such technologies across spatial and temporal scales. Crop growth simulation models are useful tools to assess the impact of environment, crop management, genetics and breeding strategies, as well as climate change and variability on growth and yield (Boote et al., 2001; Craufurd et al., 2011). The need to accurately model effects of climate change on crop yields has stimulated renewed interest in understanding, quantifying and modeling genetic variation in key traits or processes across scales (Craufurd et al., 2011). Thus, the potential benefit of incorporating certain traits singly or in multiple combinations for a given target environment can be assessed using crop models (Boote et al., 2001; Singh et al., 2014a,b,c).

Therefore, the objectives of this study were (1) to quantify the impact of climate change on the productivity of maize in tropical environments, and (2) to assess the potential benefits of improvement in drought and heat tolerance traits and their combination on maize yield under the current and future climates using a process-based crop model.

2. Methodology

2.1. Study sites

The sites used in this study are located in Eastern Africa (Kiboko – Kenya, Meiso, Melkasa, and Worer – Ethiopia), Southern Africa (Chiredzi and Matopos – Zimbabwe) and South Asia (Hyderabad – India). The sites are currently used by the International Maize and Wheat Improvement Center (CIMMYT) and/or its national partners as experimental sites for drought, heat and/or heat and drought research based on representativeness and facilities, and hence have compiled much of the needed data for the current study (Table 1).

The sites have different soil and climatic characteristics and hence maize varieties that differ in maturity period, stress tolerance and yield are grown across the study sites. The soils range from heavy clay to light texture with a depth ranging from 85 to 200 mm. The maize growing season across the study sites ranges from 84 to 130 days while the seasonal rainfall and reference evapotranspiration range from 170 to 550 mm and 216 to 445 mm, respectively. The mean maximum and minimum temperature range from 27.4 to 34.4 °C and 13.5 to 21.0 °C during the maize growing season in the study sites (Table 1). About 15 million hectares (Mha) of current maize growing areas have these maximum and minimum temperature ranges, and this may cover 17 Mha maize areas in 2030 (see Supplementary Material, S1).

Table 1
Characteristics of the selected research sites in Eastern and Southern Africa and South Asia.

	Eastern Africa				Southern Africa		South Asia
	Kiboko	Meiso	Melkasa	Worer	Chiredzi	Matopos	Hyderabad
Location							
Country	Kenya	Ethiopia	Ethiopia	Ethiopia	Zimbabwe	Zimbabwe	India
Latitude (°)	−2.21	9.22	8.42	9.60	−21.02	−28.38	17.62
Longitude (°)	37.82	40.76	39.32	40.45	31.58	28.50	78.65
Altitude (m)	950	1500	1540	750	438	1380	234
Soil characteristics							
Soil type	Haplic Lixisols	Eutric Vertisols	Vitric Andosols	Eutric Fluvisols	Vertic Chromic Luvisols	Glyeyic Solontez	Vertisols
Soil depth (cm)	120	132	200	200	94	85	120
Baseline climate							
Length of growing period (day)	95	90	120	84	100	120	125
Mean max. temperature (°C)	31.5	30.9	27.4	34.4	31.4	29.5	30.1
Mean min. temperature (°C)	18.5	17.3	13.5	20.1	21.0	16.2	20.3
Seasonal total rainfall (mm)	170	433	550	332	255	371	768
Season reference ET (mm)*	216	445	519	369	210	370	380
Maize Mega environment (MME) and current research focus							
MME	Dry Lowland	Dry Lowland	Dry Mid-altitude	Dry lowland	Dry Lowland	Dry Mid-altitude	Dry lowland
Current research focus	Drought & heat	Drought	Drought	Drought & heat	Drought & heat	Drought	Drought & heat

* ET = evapotranspiration.

2.2. Model description

The cropping system model (CSM) used for this study was Crop Estimation through Resource and Environment Synthesis, CERES–Maize (Jones and Kiniry, 1986), which is embedded in the Decision Support System for Agrotechnology Transfer (DSSAT), Version 4.6 (Hoogenboom et al., 2014). CERES–Maize is a process-based, management-oriented model that utilizes water, carbon, nitrogen and energy balance principles to simulate the growth and development of maize plants within an agricultural system. The model runs with a daily time step and simulates crop growth, development and yield of specific cultivars based on the effects of weather, soil characteristics and crop management practices (Jones et al., 2003).

2.3. Model input data collection

The minimum data sets required to run the DSSAT version of models and simulate a crop at a given site include location and crop characteristics, weather, soil, and crop management (Jones et al., 2003). For this study, data on maize crop management (including planting date, plant density, fertilization and irrigation) were obtained from the regional trials database of CIMMYT for the respective sites. Soil profile data of experimental stations were obtained from several sources, including field measurements, country-level secondary sources (Abebe, 1998; Nyamapfene, 1991) and the World Inventory of Soil Emission (WISE) database (Batjes, 2012, 2009). Daily rainfall, maximum and minimum temperature and radiation data of the experimental sites were obtained from meteorological stations at the study sites and/or from national meteorology service offices of countries where the study sites are located. Whenever radiation data were missing or became unavailable, estimated data provided by National Aeronautics and Space Administration-Prediction Of Worldwide Energy Resource (NASA-POWER) (http://power.larc. nasa.gov/) were used.

Maize varieties that are widely grown in the respective locations were used as benchmark varieties. The benchmark maize varieties used in this study were ZM521 (open pollinated) and WH403 (hybrid) for Eastern Africa, SC513 (hybrid) for Southern Africa and 31Y45 (hybrid) for South Asia. These are improved varieties developed by CIMMYT and/or its partners and have a combination of desired traits such as high grain yield and resistance to diseases and pests but are not considered as drought or heat tolerant (Magorokosho et al., 2010, 2009). These varieties were calibrated and evaluated for the DSSAT model previously and were used for regional studies (Tesfaye et al., 2015a).

2.4. Drought tolerance

Drought is the most common plant stress factor on the planet and over time plants have developed adaptation strategies that allow them to mitigate the negative effects of water deficits. These strategies can be classified into three broad categories: (i) drought escape (faster crop growth and completion of life cycle before the onset of drought stress), (ii) dehydration avoidance, which encompasses morpho-physiological features (e.g., deep roots, early flowering, etc.) that enable the plant, or parts thereof, to maintain hydration; and (iii) dehydration tolerance involving features that allow the plant to maintain, at least partially, proper functionality even in a dehydrated state (Levitt, 1972; Ludlow and Muchow, 1990; Turner, 1986). Since it is difficult to model all aspects of drought tolerance, in this study we focused on dehydration avoidance at the whole plant level using the root system as a means for better water access and uptake and water use efficiency. This is mainly because, at the whole plant level, rooting depth and functionality play a more critical role in dehydration avoidance than mechanisms involved in dehydration tolerance. Therefore, the root system of a maize ideotype would combine good rooting characteristics (including rapid root growth in response to water deficit) that would enable the plant to avoid dehydration and a water saving mechanism (reduced hydraulic conductivity) that would allow the plant to not quickly exhaust the limited amount of water available after the onset of drought (Passioura, 1983).

Therefore, a drought tolerant variety was considered to have greater rooting density with depth in the soil profile for greater access and extraction of soil water. The drought tolerance of the maize varieties selected for this study was, therefore, enhanced by changing the relative root distribution function (WR) and the lower limit of soil water availability (LL), which is the level of soil water below which roots cannot extract water from the soil, for each soil layer by changing the soils data file (∗.SOL) for each study site (Singh et al., 2014a). The greater rooting density for drought tolerant varieties (WR_d) was computed using Eq. 1 below as opposed to Eq. (2) which is the default in the current version of DSSAT.

$$WR_d(L) = [1.0 - Z(L)/5]^6 \tag{1}$$

where Z(L) is depth to the midpoint of soil layer.

$$WR(L) = \exp(-0.02 \times Z(L)) \tag{2}$$

As compared to Eq. (2), Eq. (1) progressively increases WR with depth in the soil profile for greater soil water extraction (Singh et al., 2014a).

A drought tolerant variety is also expected to extract water more effectively from each given layer. Thus, the available water in each soil layer was increased by 5% by reducing the lower limit (LL) of soil water extraction using Eq. (3) indicated below:

$$LL_d = LL - 0.05 \times (DUL - LL) \tag{3}$$

where LL_d is the LL for a drought tolerant variety and DUL is the drained upper limit.

2.5. Heat tolerance

Although maize is a warm season crop, it is sensitive to high temperature stress like other cereals such as rice and sorghum (Rowhani et al., 2011). Optimal temperatures for growth vary between day and night, as well as over the entire growing season; for example, during the daytime, the optimal temperatures range between 25 and 33 °C, while night temperatures range between 17 and 23 °C. Maize is highly sensitive to high temperatures (greater than 35 °C) during the reproductive period (Luo, 2011), and short episodes of high temperatures experienced around flowering can have large negative impacts on yields (Rezaei et al., 2015) due to reduced seed set and increased abortion rate. In this study, temperature tolerance was incorporated into benchmark maize varieties by modifying the temperature thresholds that affect reproductive growth.

In the current version of DSSAT, sensitivity to temperature is a species-wide trait described in the species file whereby high temperature affects grain filling rate and grain growth. Therefore, heat tolerance was incorporated into CERES-Maize model by modifying the temperature thresholds (Topt2 and Tmax) that affect the relative grain-filling rate (RGFIL). Accordingly, heat-tolerant varieties had higher (+2 °C) Topt2 and Tmax values than current maize varieties. This is similar to the method used by Singh et al. (2014c) in CERES-Sorghum. RGFIL is a temperature function computed daily with values ranging between 0 and 1. When water and nitrogen are non-limiting and temperature is in the optimum range, RGFIL has a value of 1 and daily kernel growth is equal to the genetic coefficient G3. If RGFIL becomes zero due to temperature stress, kernel growth stops and grain weight does not increase (López-Cedrón et al., 2005).

2.6. Drought and heat tolerance

Drought and heat tolerance were incorporated into maize varieties by combining the drought and heat tolerance traits mentioned above.

2.7. Climate change scenarios

There is greater likelihood that temperatures in Africa will increase faster than the global average, particularly in the more arid regions. Accordingly, temperature increase is projected to exceed 2 °C by 2050 across much of Africa and reach between 3 and 6 °C by the end of the century (Niang et al., 2014). On the other hand, projected rainfall change over SSA in the mid- and late 21st century is uncertain although dry and extreme conditions are likely in the southern and eastern parts of SSA, respectively (Niang et al., 2014). Because of these uncertainties related to rainfall projections, the following three climate change scenarios were considered in this study:

(1) baseline climate (2000–2009) from measured data;
(2) future climate scenarios whereby mean temperature increases by 1, 2 and 4 °C from the baseline climate with no change in rainfall conditions (referred hereafter as *hotter climate scenarios*); and

Table 2
Summary of climate scenarios and crop traits used in the study.

No.	Climate scenario	Data type	No.	Variety	Traits
1	Baseline climate	Historical climate	1	Benchmark	Commonly grown standard check
2	Hotter climate	Temperatures increase by 1, 2, 4 °C from baseline and baseline rainfall	2	Drought tolerant	Drought tolerance traits incorporated into benchmark varieties
3	Hotter and drier climate	Temperatures increase by 1, 2, 4 °C and rainfall decreases by 20% from baseline	3	Heat tolerant	Heat tolerance traits incorporated to benchmark varieties
			4	Drought & heat tolerant	Both drought and heat tolerance traits incorporated into benchmark varieties

(3) future climate scenarios whereby mean temperatures increase by 1, 2 and 4 °C and rainfall decreases by 20% from baseline climate (referred here after as *hotter and drier climate scenarios*).

The 1, 2 and 4 °C increases refer to projected temperatures increases in 2030, 2050 and beyond 2050, respectively. Hence, the climate changes scenarios were incorporated into the maize model as addition of changes in maximum and minimum temperature (delta values), and multiplication of changes in rainfall over the baseline climate in the 'environmental modifications section' of the management files of maize (∗.MZX). As summary of the climate scenarios and varietal traits studied is presented in Table 2.

2.8. Model evaluation

The CERES-Maize model was evaluated using maize experimental data collected at Muzarabani (16.36 S & 32.02 E), Zimbabwe under optimum management (irrigated and well fertilized), and drought and heat stress conditions in 2014 & 2015 during the off season. The heat stresses were imposed by varying planting dates. Model performance was evaluated using root mean square error (RMSE) and index of agreement (d) (Willmott, 1982).

2.9. Estimation of the impact of climate change and stress tolerance traits

The maize model in DSSAT v4.6 was run in seasonal mode to simulate the impact of climate change on maize productivity. Simulations were made for the baseline climate, the hotter climate scenarios and the hotter and drier climate scenarios under constant CO_2 concentration of 380 ppm.

The sowing date windows used in the simulation were from mid-June to mid-July for the sites in northern hemisphere and from mid-October to mid-November for the sites in the southern hemisphere. The soil profiles were considered at 50% of drained upper limit (DUL) at the time of sowing. The maize varieties were simulated using a plant population of 5.3 plants m^{-2} with a row-spacing of 75 cm. Simulations were carried out under optimum nutrient supply conditions in order to avoid confounding effects.

2.10. Estimation of impact

The potential impact of climate change was estimated by calculating relative changes in maize yield between baseline and future climate scenarios as follows (Eq. 4):

$$\Delta Y = \frac{(Y_{fi} - Y_b)}{Y_b} \tag{4}$$

where ΔY is change of yield, Y_{fi} is yield under future climate i, and Y_b is yield under the baseline climate.

Like benchmark maize varieties, heat, drought and combined heat and drought tolerant varieties were simulated under baseline and future climate conditions as described above. The benefit from stress tolerance was estimated by comparing the simulated yield of stress-tolerant maize varieties with benchmark varieties under a given set of climate as follows (Eq. 5):

$$\Delta Y = \frac{(Y_{si} - Y_{bi})}{Y_{bi}} \tag{5}$$

where ΔY is change of yield, Y_{si} is the yield of the stress tolerant maize variety under climate i, and Y_{bi} is the yield of the current maize variety under climate i.

2.11. Potential farmer level acceptability

Adoption of new varieties by farmers is not automatic or cost free. To potentially reap the benefits of new varieties, farmers face transaction costs when switching to these new varieties. These transaction costs include higher costs in obtaining new seeds, learning and adaptation costs and the uncertainty in expected yields related to adopting a new variety. Moreover, decision making by farmers in developing countries is very much related to risk management. This means that not only the mean yield is important but also the distribution of yields across expected plausible and probable weather patterns.

For every site and each climate scenario we predict the transaction cost threshold (or break-even) that would inhibit the adoption of alternative varieties. We also determine for each site and climate scenario which variety best fits into the system under risk aversion using the following equation (Eq. 6):

$$E(Y_i) = \sum_{n \in \{low, mean, high\}} [Prob_n * (1 - penalty) * Y_{in}] \tag{6}$$

where $E(Y_i)$ is the expected benefit from the yield, n is state of nature, $Prob_n$ is the probability of occurrence of the states of nature and Y_{in} is yield under different states of nature under specified climate change scenarios.

The importance of transaction costs for technology adoption is recognized (Cuevas, 2016; Emerick et al., 2016; Pender and Kerr, 1998; Poulton et al., 2006; Sadoulet and De Janvry, 1995; Teklewold et al., 2013; Wossen et al., 2015) but determining the exact level of these transaction costs is difficult. In our analysis we assume that transaction costs associated with adoption of new varieties, as compared to non-adoption, is at least 10% and are typically around 20% as a rule of thumb. The simulation results allow us to work backward from the predicted benefits to predict the transaction cost (maximum) threshold that would inhibit the adoption of each variety in each scenario. Very high predicted thresholds that amply surpass the 20% transaction costs rule of thumb make adoption very likely, whereas predicted thresholds of less than 10% are assumed not to succeed. Varieties with predicted transaction cost thresholds lying between 10% and 20% might still be adopted, and those with predicted thresholds between 20% and 30% are very likely to be adopted. Varieties that can have predicted thresholds greater than 30% are extremely likely to be adopted.

3. Results

3.1. Model evaluation

A comparison of measured and simulated yields under optimum management, drought stress and heat stress conditions showed good agreement between the measured and simulated values (Fig. 1).

The RMSE values were 0.94, 0.56 and 1.14 t ha^{-1} and the d-index values were 0.94, 0.90 and 0.82 for the optimum management, drought stress and heat stress conditions, receptively. The evaluation indicates a good performance of the model in capturing the response of maize to different environments conditions.

3.2. Response of maize to temperature and rainfall conditions

Grain yield decreased as total seasonal rainfall decreased (Fig. 2a). For every 100 mm reduction in total season rainfall, grain yield reduced by approximately 1263 kg ha^{-1}.

Mean seasonal temperature was negatively related to grain yield within the temperature ranges recorded at the study sites (Fig. 2b). With a 1 °C increase in mean seasonal temperature, grain yield was reduced by nearly 500 kg ha^{-1} (approximately 7%). Thus, deviations in rainfall and/or temperature conditions from the current climate will affect the growth and development of maize differently and can cause considerable yield losses as presented below.

3.2.1. Impact of temperature increase on maize yield

Relative to the baseline climate, the hotter climate change scenarios caused considerable maize yield reduction across the study sites (Fig. 3a). However, the magnitude of the impact varied with the level of temperature increase and study sites.

An increase in mean air temperature by 1, 2 and 4 °C relative to the baseline climate resulted in a yield reduction of 1–21%, 3–34% and 17–67%, respectively. The sensitivity of maize yield to increasing temperature levels under the hotter climate change scenarios was higher at hotter locations (Hyderabad, Chiredzi, Worer and Kiboko) than at relatively cooler sites (Matopos, Meiso and Melkasa) (Fig. 3a).

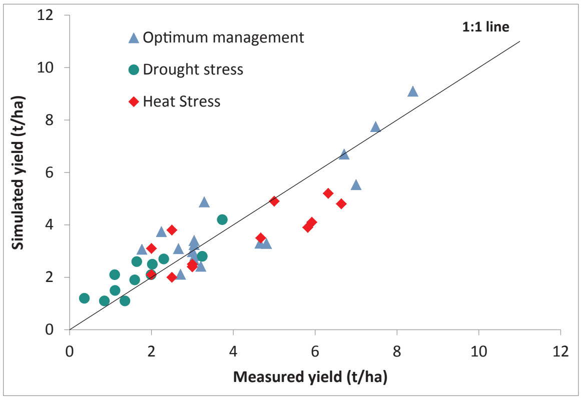

Fig. 1. Comparison of measured and simulated yields of maize varieties grown under optimum, drought and heat stress environments.

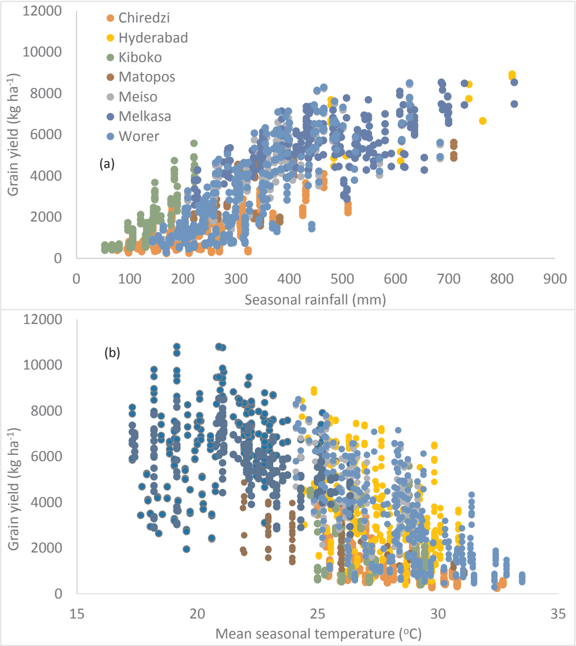

Fig. 2. The relation between simulated maize yield and (a) seasonal rainfall total and (b) mean air temperature under baseline and future climate scenarios. The data are from seven sites and ten seasons for benchmark, drought, heat, and combined drought & heat tolerant varieties.

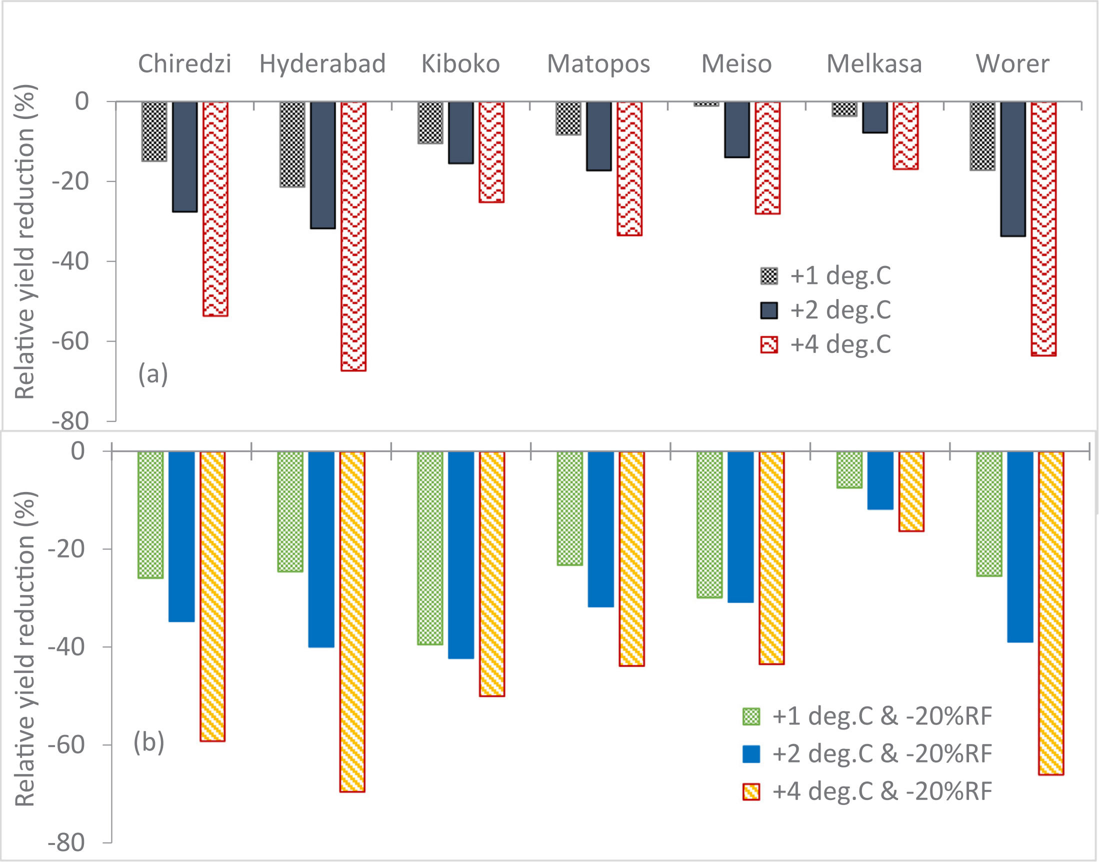

Fig. 3. Relative reductions in simulated maize yield in response to (a) hotter climate scenarios (temperature increase only) and (b) hotter and drier climate scenarios (temperature increase and rainfall [RF] decrease) at different maize growing sites relative to the baseline climate period (2000–2009).

Table 3
Simulated maize yields (mean and standard deviation [std dev], kg ha^{-1}) and relative yield changes due to drought, heat and combined drought & heat tolerance (compared to benchmark maize varieties) under the baseline climate at maize experimental sites in Eastern and Southern Africa and South Asia.

Site	Benchmark		Drought tolerant			Heat tolerant			Drought & heat tolerant		
	Yield	Std dev	Yield	Std dev	% change	Yield	Std dev	% Change	Yield	Std dev	% Change
Chiredzi	1327	905	1558	963	17.4	1383	900	4.2	1626	957	22.5
Hyderabad	3908	1627	6177	1660	58.1	3930	1630	0.6	6179	1665	58.1
Kiboko	2395	1741	2456	1741	2.5	3976	1741	66.0	4330	1771	80.8
Matopos	3124	1211	3156	1275	1.0	3147	1190	0.7	3179	1190	1.7
Meiso	4589	2335	4874	1638	6.2	4615	2132	0.6	4863	2129	6.3
Melkasa	6026	1247	6358	1029	5.5	6030	568	0.1	6370	815	5.7
Worer	2706	1407	3100	1502	14.5	3100	1502	14.5	5397	2129	99.4

3.2.2. Impact of temperature increase and rainfall decrease on maize yield

The hotter and drier climate change scenarios which involved an increase in mean air temperature with reduction in rainfall amount caused a higher yield reduction than the hotter climate scenarios that involved only temperature increases (Fig. 3b). Relative to the baseline climate, the hotter and drier climate with a mean temperature increase of 1, 2, and 4 °C reduced simulated yield by a range of 7–39%, 12–42% and 16–70% across the study sites, respectively. On average, the future drier climate would reduce maize yield by 25%, 33% and 50% across the study sites under a rise of temperature by 1, 2 and 4 °C, respectively.

3.3. Benefit of incorporating drought tolerance under the current and future climate

Incorporation of drought tolerance into maize varieties increased simulated yields under both the baseline and future climate conditions. Under the baseline climate, the relative yield advantage of drought tolerant maize varieties ranged 1–58% across the study sites (Table 3).

Drought tolerance also played a positive role under the hotter climate change scenarios with the relative yield values ranging between 1 and 72%, 2 and 68% and 4 and 84% under a mean air temperature increase of 1, 2 and 4 °C, respectively (Table 4). Relative to the benchmarks, heat tolerant varieties increased yields by 2–53%, 3–60% and 4–62% under the hotter & drier climate scenarios with a temperature increase of 1, 2 and 4 °C, respectively (Table 5).

Although drought tolerance increases yield at all the sites studied under the current and future climate conditions, the magnitude

Table 4
Simulated maize yields (mean and standard deviation [std dev], kg ha^{-1}) and relative yield changes due to drought, heat and combined drought & heat tolerance (compared to benchmark maize varieties) under hotter climate change scenarios (temperature changes) at maize experimental sites in Eastern and Southern Africa and South Asia.

Site	Benchmark		Drought tolerant			Heat tolerant			Drought & heat tolerant		
	Yield	Std dev	Yield	Std dev	% Change	Yield	Std dev	% Change	Yield	Std dev	% Change
Temperature increase by 1 °C											
Chiredzi	1129	802	1338	851	18.5	1206	812	6.8	1443	856	27.8
Hyderabad	3074	1666	5296	1462	72.3	3195	1654	3.9	5348	1492	74.0
Kiboko	2145	1418	2186	1488	1.9	3596	1418	67.6	3657	1487	70.5
Matopos	2865	974	2895	1060	1.1	2897	938	1.1	2927	1026	2.2
Meiso	4540	2373	4799	2406	5.7	4953	2025	9.1	5253	2027	15.7
Melkasa	5807	1064	6038	984	4.0	5891	568	1.4	6154	641	6.0
Worer	2242	1194	2535	1271	13.1	2833	1598	26.4	4816	2027	114.8
Temperature increase by 2 °C											
Chiredzi	961	721	1129	769	17.5	1070	762	11.4	1262	791	31.4
Hyderabad	2667	1716	4489	1635	68.3	2673	1721	0.2	4527	1693	69.7
Kiboko	2024	1458	2103	1530	3.9	3658	1460	80.7	3849	1532	90.2
Matopos	2586	901	2625	975	1.5	2624	853	1.5	2664	929	3.0
Meiso	4448	2282	4659	2304	4.7	4480	1708	0.7	4804	1732	8.0
Melkasa	5556	1083	5850	1113	5.3	5586	880	0.5	5901	885	6.2
Worer	1795	948	2008	1015	11.8	2371	1395	32.1	4234	1732	135.9
Temperature increase by 4 °C											
Chiredzi	616	514	681	544	10.6	754	603	22.4	845	639	37.2
Hyderabad	1279	711	2349	1412	83.6	1510	808	18.1	2754	1702	115.3
Kiboko	1792	1278	1859	1411	3.7	2048	1425	14.3	2165	1571	20.8
Matopos	2080	967	2173	1001	4.5	2125	906	2.2	2219	938	6.7
Meiso	3400	1857	3570	1890	5.0	3457	1271	1.7	3662	1342	7.7
Melkasa	5007	1300	5274	1290	5.3	5165	1192	3.2	5393	1228	7.7
Worer	988	626	1067	664	8.0	1408	899	42.5	3176	1342	221.5

Table 5
Simulated maize yields (mean and standard deviation [std dev], kg ha^{-1}) and relative yield changes due to drought, heat and combined drought & heat tolerance (compared to benchmark maize varieties) under hotter and drier climate change scenarios (temperature and rainfall changes) at maize experimental sites in Eastern and Southern Africa and South Asia.

Site	Benchmark		Drought tolerant			Heat tolerant			Drought & heat tolerant		
	Yield	Std dev	Yield	Std dev	% Change	Yield	Std dev	% Change	Yield	Std dev	% Change
Temperature increases by 1 °C *and rainfall decreases by* 20%											
Chiredzi	984	712	1141	772	16.0	1057	721	7.4	1225	768	24.5
Hyderabad	2950	1537	4512	1515	53.0	2970	1499	0.7	4510	1557	52.9
Kiboko	1450	952	1605	1021	10.7	1457	952	0.5	1603	1018	10.5
Matopos	2399	970	2440	1055	1.7	2425	945	1.1	2465	1032	2.8
Meiso	3220	2099	3365	2114	4.5	3297	1931	2.4	3454	1965	7.3
Melkasa	5579	542	5829	504	4.5	5579	417	0.0	5854	618	4.9
Worer	2018	1113	2587	1367	28.2	3463	1489	71.6	5042	1965	149.9
Temperature increases by 2 °C *and rainfall decreases by* 20%											
Chiredzi	867	629	989	708	14.1	963	664	11.1	1105	733	27.5
Hyderabad	2348	1407	3765	1645	60.4	2429	1461	3.5	3881	1637	65.3
Kiboko	1385	1007	1487	1074	7.4	1434	1007	3.5	1525	1051	10.1
Matopos	2134	844	2191	888	2.7	2165	850	1.4	2222	933	4.1
Meiso	3178	2020	3309	2057	4.1	3440	1681	8.3	3755	1778	18.2
Melkasa	5318	574	5547	720	4.3	5381	574	1.2	5563	745	4.6
Worer	1654	910	2052	1087	24.0	3063	1319	85.2	4711	1778	184.8
Temperature increases by 4 °C *and rainfall decreases by* 20%											
Chiredzi	542	438	610	476	12.5	662	517	22.1	758	560	39.9
Hyderabad	1191	608	1934	1021	62.3	1533	899	28.7	2520	1324	111.5
Kiboko	1198	945	1320	986	10.2	1459	1055	21.8	1641	1134	37.0
Matopos	1756	844	1832	888	4.3	1794	796	2.1	1870	841	6.5
Meiso	2596	1636	2687	1666	3.5	2803	1255	8.0	2886	1330	11.2
Melkasa	5044	1216	5165	1323	2.4	5084	999	0.8	5173	1093	2.6
Worer	919	575	1120	679	21.9	2190	854	138.3	3939	1330	328.7

varies among the sites and climate scenarios. The sites that benefit more from growing drought tolerant varieties under the current and future climate conditions are Hyderabad, Chiredzi, Kiboko, and Worer (Tables 3–5). Combined heat & drought stress tolerance has previously been shown not to be related to drought tolerance alone (Cairns et al., 2013a), thus drought tolerance alone did not significantly increase relative yield under the hotter and drier climate as compared to the hotter climate scenarios (Tables 4 and 5).

3.4. Benefit of heat tolerance under the current and future climate

Relative to benchmark varieties, heat tolerant varieties increased maize yields at most of the sites studied under the baseline and future climate conditions (Tables 3–5). The sites that benefit from heat tolerant varieties under the baseline climate are Kiboko and Worer (15–66%) as compared to the rest of the study sites (0.1–0.7%). However, the benefit from heat tolerant varieties increased and expanded to other areas (e.g., Chiredzi, Hyderabad and Meiso) as the mean temperature increased from 1 to 4 °C under the hotter climate scenarios (Table 4). Under the hotter and drier climate scenarios, Worer had the highest yield benefit followed by Chiredzi, Hyderabad and Kiboko, particularly under the 4 °C increase (Table 5).

3.5. Benefit of combined heat & drought tolerance under the current and future climate

Incorporation of heat and drought tolerance into maize varieties increased yield by 2–99% under the baseline climate and by 2–115%, 3–136% and 7–222% under the hotter climate change scenarios that involved a mean temperature increase of 1, 2 and 4 °C, respectively (Tables 3 and 4). The benefit from combined heat & drought tolerance under the baseline climate and the hotter climate scenarios was greater at Worer, Chiredzi, Hyderabad, and Kiboko than at Matopos, Meiso and Melkasa (Tables 3 and 4). Similarly, varieties with combined heat & drought tolerance traits increased maize yield by 3–150%, 4–185% and 7–329% under the hotter and drier climate change scenarios with a mean temperature increase of 1, 2, and 4 °C, respectively (Table 5). The benefits of combined heat & drought tolerance are also greater at Worer, Hyderabad, Chiredzi and Meiso but smaller (< 7%) at Matopos and Melkasa under the hotter and drier climate change scenario. Moreover, the benefit from combined heat & drought tolerance increased with an increase in temperature levels under both the hotter, and hotter and drier climate change scenarios (Tables 4 and 5).

3.6. Potential farmer level acceptability of stress tolerant varieties

Analysis of potential farmer level acceptability of the simulated drought, heat, and drought & heat tolerant varieties indicates that under risk aversion but no transaction costs the new varieties outperform the benchmark varieties, which was already apparent from the previous tables. The transaction cost cut-off points for each site and climate scenario are provided in Table 6. Across sites,

Table 6
Preferred varieties by farmers under risk management with no transaction costs.

Site	Preferred variety under no transaction costs	Transaction cost threshold level that inhibits adoption	Preferred variety under no transaction costs	Transaction cost threshold level that inhibits adoption
Temperature increases by 1 °C			Temperature increases by 1 °C and rainfall decreases by 20%	
Chiredzi	Drought & heat tolerant	29%	Drought & heat tolerant	26%
Hyderabad	Drought & heat tolerant	46%	Drought tolerance	39%
Kiboko	Drought & heat tolerant	48%	Drought tolerance	11%
Matopos	Drought & heat tolerant	2%	Drought & heat tolerant	3%
Meiso	Drought & heat tolerant	18%	Drought & heat tolerant	12%
Melkasa	Drought & heat tolerant	7%	Drought & heat tolerant	5%
Worer	Drought & heat tolerant	56%	Drought & heat tolerant	63%
Temperature increases by 2 °C			Temperature increases by 2 °C and rainfall decreases by 20%	
Chiredzi	Drought & heat tolerant	32%	Drought & heat tolerant	26%
Hyderabad	Drought & heat tolerant	47%	Drought & heat tolerant	45%
Kiboko	Drought & heat tolerant	54%	Drought & heat tolerant	13%
Matopos	Drought & heat tolerant	3%	Drought & heat tolerant	4%
Meiso	Drought & heat tolerant	12%	Drought & heat tolerant	22%
Melkasa	Drought & heat tolerant	7%	Drought & heat tolerant	5%
Worer	Drought & heat tolerant	60%	Drought & heat tolerant	68%
Temperature increases by 4 °C			Temperature increases by 4 °C and rainfall decreases by 20%	
Chiredzi	Drought & heat tolerant	35%	Drought & heat tolerant	35%
Hyderabad	Drought & heat tolerant	52%	Drought & heat tolerant	53%
Kiboko	Drought & heat tolerant	17%	Drought & heat tolerant	35%
Matopos	Drought & heat tolerant	8%	Drought & heat tolerant	8%
Meiso	Drought & heat tolerant	13%	Drought & heat tolerant	17%
Melkasa	Drought & heat tolerant	8%	Drought & heat tolerant	3%
Worer	Drought & heat tolerant	72%	Drought & heat tolerant	> 75%

simulated drought & heat tolerant varieties generally perform best under risk management and no transaction costs. Only in the case of Hyderabad and Kiboko with temperature increases by 1 °C and rainfall decreases by 20%, does the drought tolerant varieties do better.

In Worer and Hyderabad, the predicted (maximum) transaction cost cut-off points are high for the stress tolerant varieties, making them extremely likely to be adopted under all climate scenarios. In Chiredzi, adoption is also highly likely in most climate scenarios. The results are more mixed and dependent on the climate scenario in Kiboko. In Meiso, the prospects of adoption of stress tolerant varieties are not very promising although there may be scope for adoption under a few climate scenarios. The new simulated stress tolerant varieties do not offer enough improvement over the benchmark varieties in Melkasa and Matopos – making prospective adoption unlikely (Table 6).

4. Discussion

Crop models are currently the best tools available to investigate how crops will respond to and grow under future climatic conditions (Matthews et al., 2013; Rezaei et al., 2015). Similar to previous works (e.g., Singh et al., 2014a,b,c), this study used a crop model to quantify the impact of climate change on maize yields and also evaluated the impact of selected drought and heat tolerance traits and their combination under baseline and future climate change scenarios in tropical maize environments.

4.1. Impacts of climate change

The study results indicated an alarming impact of climate change on maize production in the study sites. Considerable maize yield reductions are observed under the hotter climate scenarios although the degree of the impact vary across sites and level of temperature increases. Similarly, previous studies showed that an increase in temperature by 2 °C would result in a greater reduction in maize yields than a decrease in precipitation by 20% (Lobell and Burke, 2010). A study in Tanzania also projected that an increase in temperature by 2 °C reduced maize yields by 13% which is higher than increased intra-seasonal rainfall variability (Rowhani et al., 2011). It is indicated that a further 1 °C of warming would cause yield losses in about 65% and 100% of maize-growing areas in Africa under optimal rainfed management and drought conditions, respectively (Lobell et al., 2011). Moderate to severe yield reductions were also reported when the average temperature exceeded the 18–20 °C threshold across maize growing areas in Eastern Africa under climate change (Thornton et al., 2009).

Even more alarming are the impacts under the hotter and drier climate change scenarios. As expected, the combination caused greater reductions in maize yield across the study sites except Melkasa. The average negative impact of hotter and drier climate on maize yield was 2.3, 1.6 and 1.2 times that of the impact in the hotter climate scenarios under a temperature rise of 1, 2, and 4 °C, respectively indicating that heat stress could be equally as important as drought for maize production when current mean air temperatures increase beyond 2 °C. Higher temperatures are often associated with increases in evapotranspiration which hasten the onset and severity of drought stress, especially in rainfed drylands. In addition, a hotter climate would shorten the crop cycle (more rapid crop growth, ceteris paribus), thereby reduce the yield potential (Rezaei et al., 2015). This study reiterates earlier findings that the combined effect of heat and drought on yield of many crops is stronger than the effects of each stress alone (Cairns et al., 2012; Dreesen et al., 2012; Lipiec et al., 2013; Rollins et al., 2013) as the combined effect exceeds the sum of the effects of the individual stresses (Barnabás et al., 2008; Cairns et al., 2013a; Rizhsky et al., 2002, 2004). For example, a meta-analysis of crop model simulation studies in West Africa indicated a median yield loss of 21% under a temperature increase with a decrease in rainfall and a 15% loss under a temperature increase without a decrease in rainfall across all crops in the region (Roudier et al., 2011).

There was spatial variation in the sensitivity of maize yield to changes in temperature and/or rainfall. For example, the impact of hotter climate is greater at Hyderabad, Chiredzi, Kiboko and Worer than at Matopos, Meiso and Melkasa whereas the impact of hotter and drier climate was similar across the study sites except Melkasa. Maize growing areas in the semi-arid tropical environments which already have hot and dry climate conditions, could thus lose at least one-third of their maize production in the near future unless adaptation measures are taken. This is in line with previous reports that indicated greatest reduction in maize yield in the dry and wet lowland maize mega environments in SSA (Jones and Thornton, 2003; Tesfaye et al., 2015a) and South Asia (Tesfaye et al., 2016).

4.2. Benefit of incorporating drought & heat tolerance

Incorporating drought, heat and combined drought & heat tolerance into benchmark maize varieties has clear benefits under both the current and future climate conditions. However, the benefits vary across the study sites (depending upon the amount and distribution of rainfall and water retention capacity of soils at the sites), and climate change scenarios. Under the baseline climate, Hyderabad had the highest relative yield gain from drought tolerant varieties while Kiboko and Worer had the highest benefit from heat tolerance and combined drought & heat tolerance, respectively. Hyderabad benefits most from drought tolerance while Worer followed by Kiboko gain the most from heat tolerance under both hotter and hotter and drier climate scenarios. On the other hand, there were limited simulated benefits from drought, heat and the combined traits at Matopos and Melkasa under the current and future climate change scenarios due to the fact that current temperatures at these sites are within the optimum temperature thresholds for maize and future increases will not be as stressful. The results also showed that the benefit from combined drought & heat tolerance is larger than the benefit from either drought or heat tolerance at most of the study sites. Another important aspect of the results is that the benefit from stress tolerance varieties has a limit. For example, the benefit from heat tolerance at Kiboko declined as warming over the current climate exceeds 2 °C. Kiboko already represents stressed maize production and hence transformative changes, such as moving to other crops (or even out of cropping), is likely to be an important feature of adaptation to climate change.

In general, the simulation results indicate that stress tolerant varieties can benefit farmers under the changing climate while the benefit can vary depending on current climate and soil properties of the production environment and the magnitude and type of future climate change. Therefore, besides developing new stress tolerant varieties, the results suggest the need for proper targeting of the new varieties where they fit best and benefit most (Tesfaye et al., 2015b). Since our simulations are made under optimum soil nutrient conditions in order to avoid the confounding effect of nutrient stress stresses, the observed benefits from stress tolerant varieties could be overestimated. However, a comparison of the relative yield advantages of drought estimated under the baseline climate from this study with previous reports from field experiments indicates that the estimated values are within the range of values found under field conditions. For example, drought tolerant maize hybrids developed by CIMMYT in Southern Africa had up to 40% yield advantage compared to commercially available hybrids (Cairns et al., 2013a), a result of concerted effort in directed selection for drought tolerance using multi-location trials for over four decades (Edmeades, 2008).

Studies indicate that about 25% of losses due to drought can be eliminated by genetic improvement in drought tolerance (Edmeades, 2008). Although drought tolerance in maize could be attributed to multiple plant traits, only root traits are simulated in this study mainly because a deep root system is one of the major traits to select for drought tolerance in maize (Ribaut et al., 2009). Maize responds to drought stress by redirecting resources away from the shoot to the root (Ribaut et al., 2009; Sharp et al., 2004). This shift involves an increase in root cell wall extensibility at the root tip and result in sustained growth of the root in the face of decreased water potential (Ober and Sharp 2007). Roots also provide the hydraulic environment that allow plants to control processes of leaf development and stomata opening and thereby maximize water use during critical stages (Vadez, 2014). Studies suggest that a combination of high water use efficiency and sufficient water acquisition by a deep root system can increase drought tolerance in maize (Hund et al., 2009) and give yield advantages over drought susceptible genotypes. Genotypic variation for root traits exists in maize (Li et al., 2015; Trachsel et al., 2011), which can be utilized for developing drought tolerant cultivars.

As episodes of high temperature experienced during reproductive development can have large negative impacts on cereal grain yields (Rezaei et al., 2015), heat tolerance was modelled in the current study by increasing the temperature thresholds that affect reproductive development, particularly grain growth. Several studies have found that high temperatures are damaging to several processes including maize pollen viability (Dupuis and Dumas, 1990; Schoper et al., 1987), potential kernel growth rate and final kernel size (Jones et al., 1984) and grain sink strength and yield (Commuri and Jones, 2001).

In general, drought stress usually goes along with high temperature and hence drought and heat tolerant crops will play an increasingly important role in hotter and drier production environments. Therefore, as breeding for plant productivity under stress advances, there is a need to consider whole plant stress tolerance strategies against multiple combined stresses in a systems approach (Comas et al., 2013).

4.3. Adoption potential

Transaction costs are a major determinant of technology adoption. The simulation results predicted the (maximum) transaction cost threshold that would inhibit the adoption of each variety in each scenario. Predicted transaction cost cut-off points of below 10% imply that the new variety will not likely be adopted (given that actual transactions costs are likely to be higher – thus making adoption uneconomical). If the predicted threshold is over 30%, it will almost surely be adopted; and predicted levels that lie between 10 and 30% need more socio-economic analysis, especially when below 20%. From the perspective of potential farmer acceptance the simulated benefits of new varieties under risk management indicate that varieties with different climate change adaptation traits are suited for different climate scenarios and sites. When we take into consideration the role of predicted transaction cost thresholds in the adoption of new technologies, adoption is likely in Chiredzi, Hyderabad and Worer. On the other hand, adoption is unlikely in Matopos and Melkasa while the picture is mixed for Kiboko and Meiso.

4.4. Limitations of the study

Our simulation study involved some important assumptions. Firstly, CERES-Maize does not include crop pest and disease losses, and hence these factors are assumed to be well controlled. Secondly, our study focused only on drought and heat stress tolerance and does not consider other breeding or agronomic adaptation options, for the sake of focusing on the two major components of climate change—temperature increase and rainfall variability. Thirdly, the study did not incorporate drought tolerance traits other than dehydration avoidance through better soil water extraction and water use efficiency and heat tolerance traits other than temperature resilience during grain filling because of difficulties in capturing complex traits into the current version of crop modes. Fourth, the parameterization of the sensitivity of grain growth rate to temperature in CERES-Maize was created by mimicking sensitivity of yield to elevated temperature in sorghum (Prasad et al., 2006; Singh et al. 2014c) and rice (Baker et al., 1992; Baker and Allen, 1993a,b) and hence it requires refinement based on measured data. Moreover, the potential acceptability of stress tolerant varieties by farmers only focusses on the simulated varieties in comparison to each other and does not consider issues of how the varieties fit into the broader scheme of the farming system nor other intrinsic varietal characteristics. These indicate scope and need for future studies on the adaptation of current maize-based systems to climate change in tropical environments.

5. Conclusion

Climate change threatens the production of maize in the semi-arid tropical environments which are already characterized by high temperature and variable rainfall conditions. According to the results of the present study, maize could suffer from severe yield reductions under a hotter and/or drier future climate at five of the seven sites studied. In order to maintain economically acceptable yields under the future climate in these environments, maize has to cope with drought and high temperatures. A continuous adaptation of maize to these constraints is indispensable as maize accounts for a high percentage of total cereal production and it is a key to global food security. Farmers mostly grow one or a limited number of varieties in their fields indicating the need for incorporating a good level of stress tolerance in the large majority of maize varieties that are grown under rainfed conditions. The results indicate that maize varieties that incorporate drought, heat and combined drought & heat tolerance have the potential to offset the negative impacts of hotter and/or hotter and drier conditions that are expected under climate change and improve the food security of millions of smallholder farmers in the semi-arid tropical maize growing environments. Since the benefit of each of the stress tolerance traits vary across sites and transaction costs may limit the level of adoption, there is a need for proper targeting of the new crop varieties in order to maximize their benefit and returns on investments.

Acknowledgements

This work was supported in part by the CGIAR Research Program on Policies, Institutions and Markets (PIM), The Global Futures Project funded by the Bill and Melinda Gates Foundation, CGIAR Research Program on MAIZE, and the Stress Tolerance Maize for Africa (STMA) funded by the Bill and Melinda Gates Foundation and USAID. The views expressed here are those of the authors and do not necessarily reflect the views of the authors' institutions or donors. The usual disclaimer applies.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.crm.2017.10.001.

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