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Climate change impacts and potential benefits of drought and heat tolerance in chickpea in South Asia and East Africa

Piara Singh[a,*], S. Nedumaran[a], K.J. Boote[b], P.M. Gaur[a], K. Srinivas[a], M.C.S. Bantilan[a]

[a] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru 502 324, Andhra Pradesh, India
[b] Agronomy Department, University of Florida, IFAS, Gainesville, FL 32611-0500, USA

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ABSTRACT

Using CROPGRO-Chickpea model (revised version), we investigated the impacts of climate change on the productivity of chickpea (*Cicer arietinum* L.) at selected sites in South Asia (Hisar, Indore and Nandhyal in India and Zaloke in Myanmar) and East Africa (Debre Zeit in Ethiopia, Kabete in Kenya and Ukiriguru in Tanzania). We also investigated the potential benefits of incorporating drought and heat tolerance traits in chickpea using the chickpea model and the virtual cultivars approach. As compared to the baseline climate, the climate change by 2050 (including CO_2) increased the yield of chickpea by 17% both at Hisar and Indore, 18% at Zaloke, 25% at Debre Zeit and 18% at Kabete; whereas the yields decreased by 16% at Nandhyal and 7% at Ukiriguru. The yield benefit due to increased CO_2 by 2050 ranged from 7 to 20% across sites as compared to the yields under current atmospheric CO_2 concentration; while the changes in temperature and rainfall had either positive or negative impact on yield at the sites. Yield potential traits (maximum leaf photosynthesis rate, partitioning of daily growth to pods and seed-filling duration each increased by 10%) increased the yield of virtual cultivars up to 12%. Yield benefit due to drought tolerance across sites was up to 22% under both baseline and climate change scenarios. Heat tolerance increased the yield of chickpea up to 9% at Hisar and Indore under baseline climate, and up to 13% at Hisar, Indore, Nandhyal and Ukiriguru under climate change. At other sites (Zaloke, Debre Zeit and Kabete) the incorporation of heat tolerance under climate change had no beneficial effect on yield. Considering varied crop responses to each plant trait across sites, this study was useful in prioritizing the plant traits for location-specific breeding of chickpea cultivars for higher yields under climate change at the selected sites in South Asia and East Africa.

1. Introduction

Chickpea (*Cicer arietinum* L.) is the third most important pulse crop in the world after dry beans and dry peas (Parthasarathy Rao et al., 2010). It is cultivated on 11.5 million ha with a production of 10 million tons and productivity of 863 kg ha^{-1} (mean of 2008–2010, FAOSTAT, 2012). Asia accounts for 90% of the global chickpea area. Africa accounts for 4.7% of global chickpea area and most of it is in East Africa (Ethiopia, Malawi and Tanzania). India is the largest producer of chickpea in the world. It accounts for 68% of the global area and 76% of Asia's chickpea area. Pakistan and Iran are other important chickpea-growing countries in the region. During 2008–2010, those two countries accounted for about 11% and 5% of Asia's chickpea area, respectively. Chickpea is a highly nutritious grain legume crop. It is an important source of energy, protein, minerals, vitamins, fibers and other potentially health-beneficial phyto-chemicals (Geervani, 1991). There are two types of chickpea, *desi* (light to dark brown in color) and *kabuli* type (white or beige colored seed). The *desi* type covers about 85% chickpea area and is predominantly grown in South and East Asia, Iran, Ethiopia and Australia, while Kabuli types are grown in the countries of Mediterranean region, West Asia, North Africa and North America (Gaur et al., 2008).

Although chickpea is a crop of temperate region, its cultivation is gradually spreading to sub-tropical and tropical regions of Asia, Africa, North America and Oceania. For example, Africa's share in global chickpea area has increased to 4.7% in 2008–2010 from 3.8% in 1981–1983 (FAOSTAT, 2012). In India, chickpea cultivation in the early 1970s was concentrated in the northern states of Punjab, Haryana and Utter Pradesh; western state of Rajasthan and central state of Madhya Pradesh. However, during the last few decades, with increasing availability of short- and medium-duration varieties, chickpea cultivation has expanded considerably in the hot and dry short season environments of central and peninsular India (Madhya Pradesh, Maharashtra and Andhra Pradesh) (Parthasarathy Rao et al., 2010). Terminal drought and heat stress,

* Corresponding author. Tel.: +91 040 30713334; fax: +91 040 30713074/75.
E-mail addresses: p.singh@cgiar.org, piarasingh48@gmail.com (P. Singh).

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among other abiotic and biotic stresses, are the major constraints to chickpea production in the warmer short-season semi-arid tropical environments. Also, the chickpea area under late-sown conditions, particularly in the northern and central parts of India, is increasing due to inclusion of chickpea in the sequential cropping systems, which is leading to later sowing and a prolonged exposure to heat stress during the reproductive phase of chickpea. Flowering and podding in chickpea are known to be very sensitive to the changes in external environment. Exposure to heat stress (35 °C) at these stages is known to lead to reduction in seed yield (Summerfield et al., 1984; Wang et al., 2006). Climate change, coupled with increased cultivation of chickpea in the warmer and drier environments in the future will further exacerbate the detrimental impacts of drought and heat stress on its productivity. However, in the cooler environments climate change may have a beneficial impact on the crop in the short term before the optimum temperature thresholds (20–26 °C) (Devasirvatham et al., 2012b) are exceeded. Crop yields are also expected to increase with the increase in CO_2 concentration in the atmosphere. Free air carbon enrichment (FACE) experiments showed that crop productivity could increase in the range of 15–25% for C3 crops like wheat, rice and soybean (Tubiello et al., 2007). Temperature increases are likely to support positive effects of enhanced CO_2 until temperature thresholds are reached. Beyond these thresholds, crop yields will decrease despite enhanced CO_2.

Because agriculture will not experience the same kind of vulnerability to climate change in all regions, site-specific improved crop varieties and management practices will be needed to match the characteristics of the future climates and other natural endowments of each area. Boote et al. (2011) suggested genetic improvement of crops for greater tolerance to elevated temperatures and drought, improved responsiveness to rising CO_2 and the development of new agronomic technologies to adapt crops to the current adverse climates and climate change, In case of chickpea, the plant breeders and physiologists have already identified plant traits that impart drought and heat tolerance to the crop (Krishnamurthy et al., 2010, 2011). Various sources of drought and heat tolerance traits in the germplasm accessions have been identified for breeding new varieties that are high yielding as well as having improved drought and heat tolerance. However, quantitative information on their potential benefits, in terms of yield gain, is insufficient. An early assessment of the potential benefits of these technologies would be useful before significant investments are made to pursue these goals.

Plant growth simulation models can be used to assess crop growth and yield advantages due to new technologies in different target environments. Since these models incorporate parameters representing genetic traits of cultivars, these traits can be modified within the observed limits of their genetic variability to assess the potential benefit of incorporating such traits singly or in multiple combinations for the target environment (Boote et al., 2001, 2003; Singh et al., 2012). For example, for imparting drought resistance several root traits (such as faster rate of rooting depth increase, increased root length density and deeper rooting depth) have been evaluated using crop models (Jones and Zur, 1984; Sinclair and Muchow, 2001; Boote et al., 2003; Sinclair et al., 2010); however, conflicting results have been obtained in terms of yield advantages. Singh et al. (2012) found that adaptive root traits of groundnut were useful for extracting more water from the soil profile when the crop was grown on the high water holding capacity soils than on the low water holding capacity soils of India. In the case of chickpea crop, it has also been shown that better rooting system helps increase crop yields under water stress only if it results in greater water use by the crop during the reproductive period (Zaman-Allah et al., 2011; Vadez et al., 2012). Singh et al. (2012, 2013) simulated the yield advantages of incorporating heat tolerance in groundnut under projected climate change at the selected sites in India and West Africa. Substantial yield gains for the sites were simulated when both the drought and heat tolerance traits were combined. Such simulation analyses on drought and heat tolerance of chickpea crop are lacking, especially under projected climate changes, for South Asia (India and Myanmar) and East Africa (Ethiopia, Kenya and Tanzania) environments, where chickpea is already extensively grown or because of economic advantage is becoming more popular with the farmers.

The objectives of this study were: (1) to quantify the impact of projected climate change on the productivity of chickpea at selected sites in South Asia (India and Myanmar) and East Africa (Ethiopia, Kenya and Tanzania) and (2) to assess the potential benefits of genetic improvement, particularly crop maturity duration, yield productivity traits, drought and heat tolerance traits and their combinations, on the yield of chickpea in the current and future climates at the selected sites in South Asia and East Africa.

2. Materials and methods

2.1. Study sites

For South Asia the study was carried out for three sites in India and one site in Myanmar. The sites in India were Hisar, Indore and Nandhyal, which fall in the North Western Plain Zone (NWPZ), Central Zone (CZ) and Southern Zone (SZ), respectively. These sites represent different temperature and rainfall regimes where chickpea is grown during the post-rainy season (Table 1). Mean air temperature and total rainfall during the growing season is 17.8 °C and 45 mm at Hisar, 20.4 °C and 33 mm at Indore, and 25.6 °C and 117 mm at Nandhyal, respectively. Extractable water holding capacity (EWHC) of the soils ranges from 207 to 249 mm across the sites. In Myanmar the selected site was Zaloke where chickpea crop has been recently introduced and is being increasingly grown by the farmers. Mean air temperature and total rainfall during the growing season is 23.0 °C and 62 mm, respectively. EWHC of the soil is 208 mm. In East Africa, the sites selected were Debre Zeit in Ethiopia, Kabete in Kenya and Ukiriguru in Tanzania. All the sites in East Africa are located at high elevation (1925–2097 m). Mean air temperature and total rainfall during the growing season is 17.8 °C and 72 mm at Debre Zeit, 16.4 °C and 179 mm at Kabete, and 22.4 °C and 310 mm at Ukiriguru. EWHC of the soils ranges from 202 mm to 226 mm across the sites. At all the sites in South Asia and East Africa the chickpea crop is grown after the rainy season crop on stored soil water. At all the sites typical *desi* type chickpea cultivars are grown, which are of long duration (150–160 days) in the NWPZ, medium duration (115–120 days) in the CZ and short duration (90–100 days) in the SZ zones of India. At other sites in Myanmar and East Africa the short duration types are being promoted for cultivation.

2.2. The model

We used the CROPGRO-Chickpea model (revised version) to study the impact of climate change and genetic traits on growth and yield of chickpea. The chickpea model is part of the suite of crop models available in DSSAT v4.5 software (Hoogenboom et al., 2010). The major components of the model are vegetative and reproductive development, carbon balance, water balance and nitrogen balance (Singh and Virmani, 1996). It simulates chickpea growth and development using a daily time step from sowing to maturity and ultimately predicts yield. Genotypic differences in growth, development and yield of crop cultivars are affected through genetic coefficients (cultivar-specific parameters) that are inputs to the model. The physiological processes that are simulated describe the crop response to major weather factors, including

Table 1
Geographical, soil and climatic characteristics of the selected sites in South Asia and East Africa.

	South Asia				East Africa		
	Hisar	Indore	Nandhyal	Zaloke	Debre Zeit	Kabete	Ukiriguru
Geographical characteristics							
Latitude (°)	29.1	24.72	15.48	22.20	8.73	−1.23	−2.70
Longitude (°)	75.7	75.97	78.48	95.20	38.98	36.72	33.02
Elevation (m)	247	396	282	242	2097	1925	1935
Soil characteristics							
Soil type	Entisol	Vertisol	Vertisol	Vertic Cambisol	Vertisol	Rhodic Ferralsol	Vertic Cambisol
Soil depth (cm)	168	180	200	172	140	150	150
EWHC (mm)[a]	207	236	249	208	211	226	202
Growing season climate[b]							
Mean max. temp. (°C)	26.7	29.0	31.6	29.9	26.1	22.1	28.7
Mean min. temp. (°C)	8.9	11.8	19.6	16.0	9.5	10.7	16.1
Mean temp. (°C)	17.8	20.4	25.6	23.0	17.8	16.4	22.4
Growing season							
Rainfall (mm)	45	33	117	62	72	179	310

[a] Extractable water holding capacity of soil.
[b] See Tables 2 and 3 for growing season period of chickpea.

temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. Since the publication of the paper by Singh and Virmani (1996) on adaptation of the CROPGRO model for modeling chickpea, new knowledge and findings on chickpea have been published. This required updating of the model to incorporate new research findings for better simulating the growth and development of chickpea, especially for the climate change factors. The CROPGRO-chickpea model was updated by K.J. Boote (pers. comm.) by modifying mostly the crop parameters in the species file (*.SPE) of the model. These changes were based on the research findings of Wang et al. (2006), Devasirvatham et al. (2012a) and the databases on growth and development of chickpea collected during 1985–1993 at the ICRISAT Research Center in India. The major changes made are described below:

- Temperature functions for node appearance (Fig. 1a) and internode elongation (Fig. 1b) rates affecting height and width of crop canopy were modified slightly to set node appearance and internode elongation against the observed data.
- The temperature functions for early reproductive development were slightly modified (Fig. 1c). The lower optimum temperature (Topt1) was decreased and the upper optimum temperature (Topt2) was increased to match with other cool season legumes such as fababean and common bean.
- SLAMAX and SLAMIN were set to 580 and 220 $cm^2\,g^{-1}$, respectively. The SLAMAX represents the specific leaf area (SLA) under limiting low light and the SLAMIN represents the non-stressed potential SLA under high light.
- The temperature function affecting SLA was modified to increase leaf area growth at cool temperatures and decrease leaf area growth at high temperatures, by comparison to the prior version (Fig. 1d).
- Considering a more realistic value of SLA across chickpea cultivars, the reference specific leaf weight (SLWREF) in the crop parameters was set to a value of 0.0049 $g\,m^{-2}$, this value defines the SLW (specific leaf weight) at which genetic potential leaf photosynthesis is defined.
- Maximum leaf photosynthesis rate per unit leaf area (LFMAX) in the cultivar file was set at 1.00 $mg\,CO_2\,m^{-2}\,s^{-1}$ to have a more realistic value for a winter legume crop.
- The temperature function for leaf photosynthesis was adjusted considerably to more reasonable values characteristic of cool-season winter legumes (Fig. 1e). In addition, the model allows minimum night temperature to affect the next day's photosynthesis. This is done with an asymptotic function defined by a base temperature causing zero photosynthesis rate and an optimum temperature at which there is no reduction in photosynthesis. The base and optimum were lowered from 2 and 20 °C, respectively, to −3 and 18 °C, to make the chickpea crop less sensitive to cold, than the previous version.
- Considering the findings of Wang et al. (2006), the temperature functions for pod set, seed growth rate, and partitioning limits were set, with lower values of Tb, Topt1, Topt2 and Tfailure to be more appropriate for the chickpea crop (Fig. 1f, g and h). The Tb is base temperature, Topt1 and Topt2 are lower and upper values of optimum temperature range, respectively, and Tfailure is failure temperature.
- Literature indicates that optimum soil temperatures for nodulation and N-fixation are between 18 and 22 °C (Devasirvatham et al., 2012b). The base (Tb) and optimum (Topt1) temperatures were lowered far enough so that N concentration was not excessively reduced by insufficient N-fixation (Fig. 1i). Similarly, Devasirvatham et al. (2012b) reported that nodule formation failed above 32 °C and nitrogenase did not recover when exposed to 35 °C. The upper optimum temperature (Topt2) and failure temperature (Tfailure) for high temperature effects were reduced considerably to minimize over-prediction of dry matter at high temperature (Fig. 1j).

With these changes incorporated, the model was improved in its capability to simulate growth and development of chickpea in the contrasting climatic environments, especially to study the impacts of climate change factors on chickpea crop. Under high temperatures the growth and yield of chickpea is affected through changes in crop phenology, crop growth rate and allocation of assimilates to the reproductive organs by decreased pod set and seed growth rate. Increased CO_2 concentrations in the atmosphere increase crop growth through increased leaf-level photosynthesis, which responds to CO_2 concentration using simplified rubisco kinetics similar to Farquhar and von Caemmerer (1982). The ability of the CROPGRO-based crop models to accurately predict leaf and canopy assimilation responses to CO_2 has been shown for soybean (Alagarswamy et al., 2006) and groundnut (K.J. Boote, pers. comm.). Increased CO_2 concentration reduces transpiration from the crop canopy via an empirical relationship between canopy conductance and CO_2 concentration (Boote et al., 2010). The model assumes phosphorus availability to be non-limiting for crop growth; however, it simulates nitrogen fixation by the plant and responds to insufficient soil nitrogen uptake by growing nodules and simulating N_2 fixation. It simulates the effects of both water deficits and excess on plant growth and yield. The model also assumes that the

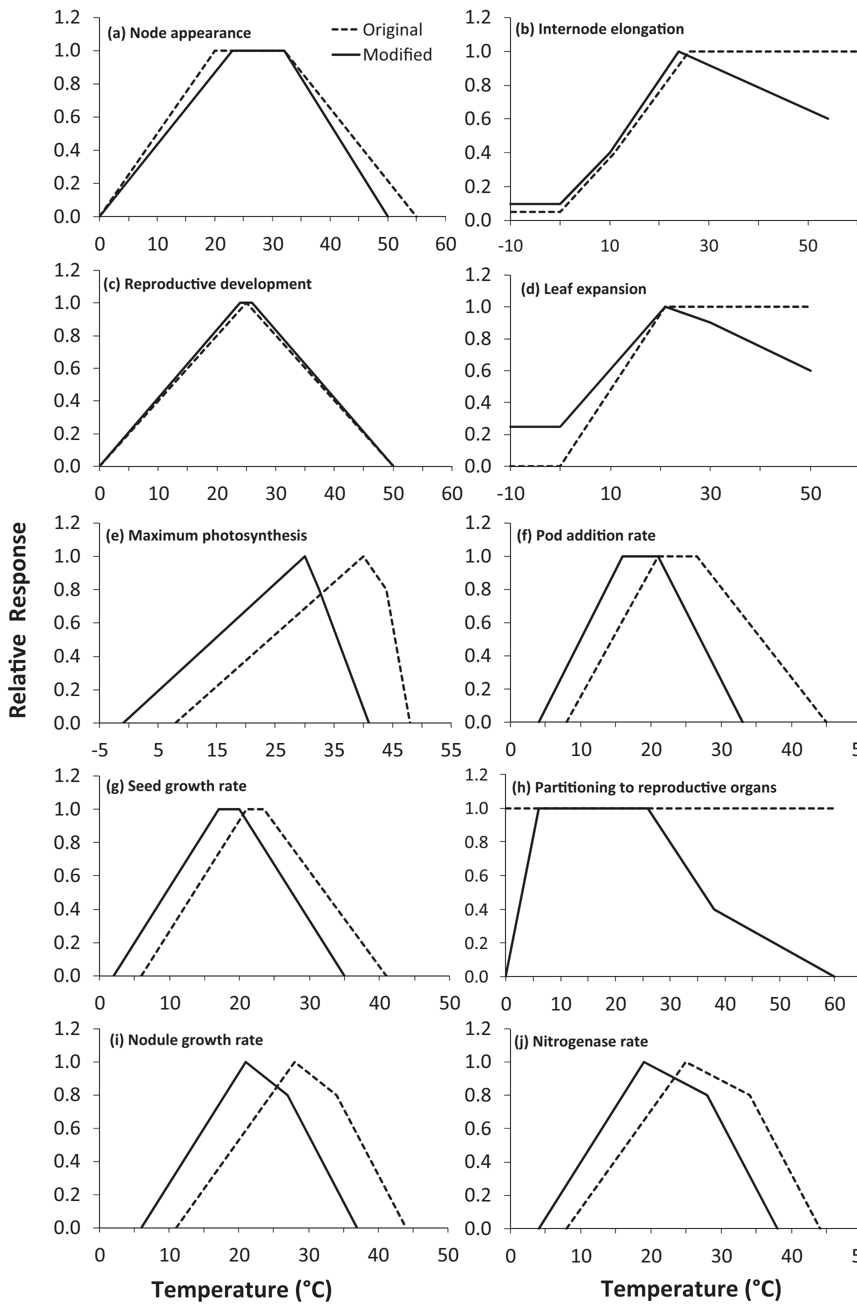

Fig. 1. Original and modified response functions to temperature for (a) node appearance, (b) internode elongation, (c) reproductive development, (d) leaf expansion, (e) maximum leaf photosynthesis rate, (f) pod addition rate, (g) seed growth rate, (h) partitioning to reproductive organs, (i) nodule growth rate, and (j) nitrogenase rate.

crop grows free of pests and diseases as it does not simulate the effects of biotic stresses on plant growth and yield.

2.3. Model inputs

The minimum data sets required to simulate a crop for a site have been described by Jones et al. (2003). Briefly, these include site location and soil characteristics, daily weather and agronomic management data. The model also needs input of cultivar-specific parameters (genetic coefficients) that distinguish one cultivar from another in terms of crop phenology, growth and partitioning to vegetative and reproductive organs and seed quality (Boote et al., 2001). The soil-profile data for the sites in India were obtained from the soil survey bulletins published by the National Bureau of Soil Survey and Land Use Planning, Nagpur, India (Lal et al., 1994). For Myanmar and the East Africa sites, the soils data were was taken from the WISE database (Batjes, 2012). Records of weather data for the sites were obtained from the India Meteorological Department (IMD) or downloaded from the NASA (http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov) or NOAA (http://www.ncdc.noaa.gov/cgi-bin/res40.pl?page=gsod.html) websites.

2.4. Model calibration of genetic coefficients

Crop data sets available in the Annual Reports of the All India Coordinated Research Project on Pulses (AICRPP, 1999–2011) were used for calibration of the chickpea cultivars. The chickpea cultivars selected were RSG 888, Vijay and JG 11 (all *desi* types). These cultivars have been used as regional checks in the multi-location rainfed trials for the past several years for evaluating new breeding lines/genotypes of chickpea. RSG 888 is a long duration variety (150–160 days) that was used in the trials conducted in the North-West Plan Zone (NWPZ) at six locations (Bawal, Diggi, Durgapura, Hisar, Samba and Srigangangar). Vijay is a medium duration variety (115–120 days) used in the Central Zone (CZ) at eight locations (Arnej, Basnwara, Badanapur, Indore, Kota, Rahuri, Raipur and Sehore). JG 11 is a short duration variety (90–100 days) used in the Southern Zone (SZ) at six locations (Lam, Warangal, Bangalore, Dharwad, Gulberga and Coimbatore). Crop data available from these trials were sowing date, days to physiological maturity, days to harvest, seed yield, and seed size. Data on other phenological stages of these varieties were available from the crop physiology trials conducted at Durgapura, Gulberga, Hisar and Jabalpur. Additional multi-location data on crop phenology of JG 11 were also available from the International Nursery Trials conducted in 2007, 2009 and 2010 (P.M. Gaur, pers. comm.). Chickpea sowing in the NWPZ and CZ zones is done after the harvest of the rainy season crop during late-October to mid-November. Normally the fields are given supplemental irrigation prior to sowing. In the SZ zone chickpea is sown after the cessation of rains during late October to mid-November and generally no irrigation is given at the time of sowing. Fertilizer is applied at the time of sowing to provide 18–25 kg N and 40–50 kg P ha^{-1}. Generally no potassium is applied. Plant population is mostly 33 plants m^{-2}.

The crop, weather and soils data of the trials were input to the standard files needed for model execution. About 50% of the data set was used for model calibration of cultivars and the remaining was saved for model validation. To calibrate cultivars, the typical genetic coefficients of the cultivar Annigeri variety were used and changes were made in the slope of the relative response of development to photoperiod below the critical day length (PPSEN) and emergence to 50% flowering (EM-FL) coefficients to match the simulated days to 50% flowering with the observed data of a cultivar recorded across sites. To calibrate the days to maturity, changes were made in the flowering to beginning shell growth (FL-SH), flowering to beginning seed growth (FL-SD) and beginning seed growth to physiological maturity (SD-PM) coefficients. Several model iterations were made until the simulated days to 50% flowering and physiological maturity were within 10% of the observed data across seasons and sites. After calibrating the growth cycle phases, the soil factor affecting growth (SLPF) and the maximum fraction of daily growth partitioned to pods (XFRT) coefficients were calibrated to match the simulated seed yield with the observed data of the sites. Simulated seed size was matched with the observed data by adjusting the coefficients of weight per seed (WTPSD), seed filling duration (SFDUR), threshing percentage (THRSH) and pod-adding duration (PODUR). Several iterations of model simulation were made to match the simulated yields of cultivars within 10–14% of the observed yields across sites and seasons. Since complete information on agronomic management and crop growth was not available for the trials, we compared only the maximum, minimum and mean seed yields simulated by the model over the years with the reported maximum, minimum and mean seed yields for the sites to evaluate model performance for both calibration and validation. We assumed that the maximum yields were obtained without any major abiotic or biotic constraints, while minimum yields were obtained under the overriding impact of drought over other types of stresses.

2.5. Development of virtual cultivars

To simulate crop response to the changes in genetic traits, virtual cultivars incorporating various plant traits were developed from the three baseline cultivars (RSG 888, Vijay and JG 11) calibrated for the Indian conditions. These are described below.

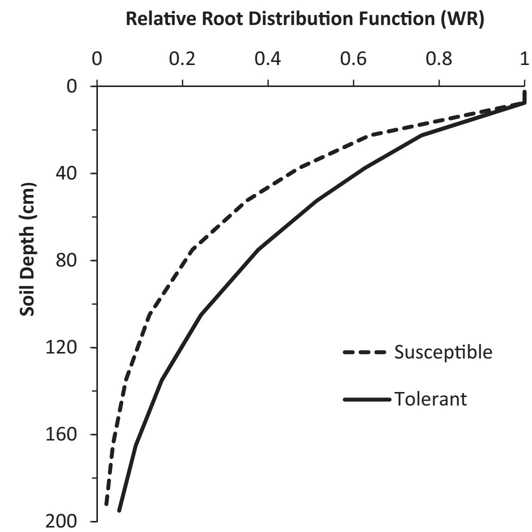

Fig. 2. Relative root distribution function (WR) with soil depth for the susceptible and tolerant cultivars.

2.5.1. Crop life cycle and yield potential traits

For developing virtual cultivars, three maturity durations of chickpea crop were considered-baseline (no change), 10% shorter maturity and 10% longer maturity. To make the crop maturity short, genetic coefficients determining emergence to 50% flowering (EM-FL), flowering to beginning seed growth (FL-SD) and beginning seed growth to physiological maturity (SD-PM) were decreased by 10% each. For the longer maturity cultivar, these coefficients were increased by 10% each. To incorporate yield potential traits in these three maturity duration cultivars, the genetic coefficients determining the maximum leaf photosynthesis rate (LFMAX), maximum fraction of daily growth partitioned to pod (XFRT) and seed-filling duration for pod cohort (SFDUR) of cultivars were increased by 10% each. There are insufficient studies to document variation across chickpea cultivars, but there is more than a 20% range of LFMAX and filling period across cultivars within soybean and groundnut, and partitioning in groundnut (see review by Boote and Tollenaar, 1994; Boote et al., 2003). This gave six virtual cultivars consisting of three with, and three without, enhanced yield potential. The genetic coefficients of these virtual cultivars were provided in the genetic coefficients file (*.CUL). To these six virtual cultivars, improved drought and heat tolerance were further incorporated as described below.

2.5.2. Drought tolerance

To enhance drought tolerance of cultivars, changes were made in the relative root distribution function (*WR*) and the lower limit of soil water availability (*LL*) for each soil layer. Currently the *WR* for different soil layers is estimated as per the following exponential equation:

$$WR(L) = exp(-0.02 \times Z(L)) \quad (1)$$

where $Z(L)$ is depth in meters to the midpoint of soil layer L. A drought resistant cultivar was assumed to have greater rooting density with depth in the soil profile for greater access and mining of soil water. The greater rooting density was computed using the following power equation:

$$WR(L) = [1.0 - Z(L)/5]^p \quad (2)$$

where p was equal to 6 and the value 5 was used for all soils. This progressively increased *WR* (over the default) with depth in the soil profile for greater soil water extraction. Fig. 2 shows the graphical representation of relative root distribution function (WR) for the drought susceptible (Eq. (1)) and tolerant (Eq. (2)) cultivars.

In addition to increased *WR* with depth, the available water in each soil layer was increased by 5% by reducing the lower limit (*LL*) of soil water extraction as follows:

$$LL(TOL) = LL - 0.05 \times (DUL - LL) \quad (3)$$

where *LL*(*TOL*) is *LL* for a drought tolerant cultivar and DUL is drained upper limit. The presumption is that a drought tolerant cultivar can extract water more effectively from each given layer. All these changes were incorporated in the soils data file (*.SOL) for each selected site.

2.5.3. Heat tolerance

Currently, heat (high temperature) tolerance is not a cultivar coefficient in the chickpea model, but rather is a species-wide trait described in the species file whereby high temperatures reduce seed set, individual seed growth rate and partitioning of assimilates to reproductive organs. Changes were made in the chickpea species file (*.SPE) to achieve a shift in tolerance to high temperature. The temperature tolerance of each of these three processes was increased by 3 °C in the species file of the chickpea model (effectively shifting the upper side of the temperature functions in Fig. 1f, g and h by 3 °C).

2.6. Projected climate change at the selected sites

Simulation of climate change impacts required projected climate change data to modify the observed weather data of sites. Statistically downscaled (delta method) projected climate data for the 2030 and 2050 time slices with 2.5 arc-minute resolution (5 km^2 resolution) and the WorldClim baseline (1960–1990) climate data with 30 arc-second resolution (1 km^2 resolution) were downloaded for the selected sites from the CIAT's climate change portal (http://ccafs-climate.org/download_sres.html – down). The projected climate data comprised of monthly values of maximum and minimum temperatures and rainfall predicted by the UKMO-HADCM3 GCM model for the SRES A1B scenario. The difference between the projected monthly maximum and minimum temperatures by 2030 and 2050 time slices and the baseline values gave changes in temperature. The percent deviations in monthly rainfall from the baseline values were also calculated (Tables 2 and 3; climate change values for 2030 not presented). Monthly changes in maximum and minimum temperature and rainfall along with CO_2 increase as per the ISAM model (IPCC, 2001) for 2030 and 2050 were input to the 'environmental modifications section' of the management files of chickpea (*.CHX). Temperatures were entered as changes in temperature (delta values), rainfall as the ratio of projected rainfall to baseline rainfall and CO_2 as an absolute value against the first day of each month. During simulations, these climate change values modified the observed baseline weather data of a given month until it read the new set of values for the next month.

2.7. Simulating the impact of climate change and genetic traits

The chickpea model coupled with the seasonal analysis program available in DSSAT v4.5 was used to simulate the impact of climate change on chickpea productivity. Simulations were carried out for the baseline climate and the projected climate change by 2030 and 2050 for each site. For each time period the impacts of change in temperature (T), changes in temperature and CO_2 (T + CO_2), and changes in temperature, CO_2 and rainfall (T + CO_2 + R) were evaluated separately to quantify the impact of each factor. The atmospheric CO_2 concentration considered was 380 ppm for the baseline climate, 454 ppm for 2030, and 530 ppm for the 2050 climate projections (IPCC, 2001). Simulation of the impact of genetic traits on the productivity of chickpea was done only for the baseline climate and climate change (T + CO_2 + R) by 2050.

At all the sites the sowing dates normally followed by the farmers in the target region were considered in the study. In the South Asia region, the sowing date for each year of simulation was 16 November at Hisar, 19 November at Indore, October 15 at Nandhyal and 25 October at Zaloke. In the East Africa region, the sowing dates were 25 September at Debre Zeit, 1 June at Kabete and 15 May at Ukiriguru. The soil profiles were considered at drained upper limit (DUL) at the time of sowing as the chickpea crop at the sites is either sown at the end of rainy season or given supplemental irrigation at sowing to support good germination and emergence. Plant population considered was 33 plants m^{-2} with a row-spacing of 30 cm. Di-ammonium phosphate (DAP) fertilizer was applied at sowing to supply 20 kg N and 40 kg P ha^{-1} to the crop. For long-term simulation of chickpea yields over the years, the soil-limited photosynthesis factor (SLPF) of 0.74 was used for Hisar, 0.84 for Indore, 0.89 for Nandhyal, 0.84 for Zaloke, 0.83 for Debre Zeit, 0.84 for Kebete and 0.86 for Ukiriguru. Site-specific values of SLPF were calibrated such that a single value of light-saturated leaf photosynthesis (AMAX) accurately predicted biomass and yield over all sites. An SLPF value less than 0.90 represents soil limitations other than N or water. Simulations were carried out for 30 years (1970–1999) for Hisar, 30 years (1975–2004) for Indore, 25 years (1984–2008) for Nandhyal, and 12 years (1997–2008) each for Zaloke, Debre Zeit, Kabete and Ukiriguru depending upon the weather data availability.

2.8. Data analysis

After calibrating the genetic coefficients of the cultivars, the observed crop yields of the cultivars were regressed against the simulated yields to determine the significance of their relationship. To validate the model performance, the observed yields of another set of data were also regressed against the simulated yields. In both cases the regression equation, coefficient of determination (R^2), residual mean standard error (RMSE) and *d*-values (Willmott, 1982) for each cultivar were determined. All the multi-year simulation output data of crop yields, evaluating the impacts of climate change and plant traits, were analyzed using analysis of variance (ANOVA) and the randomized complete block design (RCBD). Simulation years were considered as replications (blocks), as the chickpea yield in one year under a given treatment was not affected by another year (prior year carry-over of soil water was not simulated). Also, the simulation years had unpredictable weather characteristics; therefore, a formal randomization of simulation years (blocks) was not needed.

3. Results

Model calibration of baseline chickpea cultivars (RSG 888, Vijay and JG 11) showed a strong and significant relationship of observed seed yields with the simulated seed yields across the test sites (RSG 888: $y = 1.059x - 192.9$, $R^2 = 0.90$, RMSE = 192; Vijay: $y = 1.171x + 176.3$, $R^2 = 0.94$, RMSE = 153; and JG 11: $y = 1.145x - 136.0$. $R^2 = 0.84$, RMSE = 201). The *d*-value, a measure of model predictability (Willmott, 1982), was also high (0.96 for RSG 888, 0.97 for Vijay and 0.94 for JG 11). Model validation with the independent 50% of data not used in calibration, showed a significant relationship of observed yields with simulated yields across the test sites (RSG 888: $y = 0.763x + 353.5$, $R^2 = 0.81$, RMSE = 249; Vijay: $y = 0.887x + 252.8$, $R^2 = 0.81$, RMSE = 167; and JG 11: $y = 1.067x + 25.7$, $R^2 = 0.76$, RMSE = 238). The *d*-value was also

Table 2
Baseline climate and projected increase in maximum and minimum monthly temperatures and percent change in monthly rainfall during the growing season by 2050 at the selected sites in South Asia as per the UKMO-HADCM3 GCM model for the SRES A1B scenario.

Growing season	Hisar		Indore		Nandhyal		Zaloke	
	Baseline	Proj. 2050	Baseline	Proj. 2050	Baseline	Proj. 2050	Baseline	Proj. 2050
Maximum temperature (°C)								
Oct–Feb	–	–	–	–	30.0–34.0	2.1–2.4	–	–
Nov–Mar	21.9–31.2	1.3–3.1	26.3–33.7	1.9–2.9	–	–	27.0–34.8	2.7–4.1
Minimum temperature (°C)								
Oct–Feb	–	–	–	–	17.6–20.0	3.0–3.6	–	–
Nov–Mar	5.8–13.3	2.9–3.7	9.8–15.6	3.1–3.6	–	–	14.2–19.1	3.1–3.5
Rainfall (mm) and % change								
Oct	–	–	–	–	90	−14	–	–
Nov	4	0	14	14	21	100	40	13
Dec	4	−50	6	17	4	−25	8	−13
Jan	13	0	9	−11	0	0	3	33
Feb	12	0	1	0	2	−50	5	80
Mar	12	−33	3	−33	–	–	6	50

Proj.: = Projected climate change by 2050.

high (0.94 for RSG 888, 0.92 for Vijay and 0.90 for JG 11; Fig. 3). These validation results confirm that the genetic coefficients of the three baseline cultivars are accurate and the CROPGRO-Chickpea model can be reliably used to simulate growth and yield of chickpea in response to climate change factors and genetic modifications for different soil–climate environments.

3.1. Impact of climate change on chickpea yield

In the South Asia region, the baseline mean yields were 1322, 1813, 1181 and 960 kg ha^{-1} at Hisar, Indore, Nandhyal and Zaloke, respectively. Increase in temperature by 2030 at these sites increased the yields by nil to 5%, except at Nandhyal where the yield decreased by 15% (Table 4). Increase in atmospheric CO_2 concentration benefited the yields up to 11% at the sites. The net effect of climate change ($T+CO_2+R$) by 2030 was 7% increase in yield at Hisar and 11% at both Indore and Zaloke, whereas at Nandhyal the yield decreased by 4%. Further increase in temperature by 2050 increased the yield by 9% at Hisar and 1% at Zaloke and decreased by 4% at Indore and 33% at Nandhyal. The beneficial effect of increased CO_2 concentration on the yields ranged from 16 to 20% across the four sites. With the changes in temperature, CO_2 and rainfall ($T+CO_2+R$) by 2050, the net effect was up to 18% increase in yield at Hisar, Indore and Zaloke as compared to the yields simulated with the baseline climate. However, for the Nandhyal site a 16% decrease in yield was simulated, indicating that the detrimental effects of projected increase in temperatures and decrease in rainfall dominated the beneficial effects of increased CO_2 at Nandhyal. The impacts of climate change ($T+CO_2+R$) by 2030 and 2050 on chickpea yields at the South Asia sites were statistically significant ($P<0.05$) when compared with the respective baseline yields.

In the East Africa region, the baseline mean yields were 1341, 2031 and 1608 kg ha^{-1} at Debre Zeit, Kabete and Ukiriguru, respectively (Table 4). The increase in temperature by 2030 decreased the yield by 1% and 6% at Kabete and Ukiriguru, respectively; while at Debre Zeit it increased by 3%. The beneficial effect of increased CO_2 ranged from 5 to 10% across the three sites. The net effect of climate change ($T+CO_2+R$) by 2030 was 13% increase in yield at Debre Zeit, 11% at Kabete and no effect at Ukiriguru. With further increase in temperature by 2050, the yield decreased by 4% at Kabete and 13% at Ukiriguru and increased by 5% at Debre Zeit. The beneficial effect of increased CO_2 concentration ranged from 7 to 19% across the sites. The net effect of climate change ($T+CO_2+R$) by 2050 was 7% decrease in yield at Ukiriguru, 25% increase at Debre Zeit and 18% increase at Kabete. Except for the Ukiriguru site by 2030, the impacts of climate change ($T+CO_2+R$) by 2030 and 2050 on

Table 3
Baseline climate and projected increase in maximum and minimum monthly temperatures and percent change in monthly rainfall during the growing season by 2050 at the selected sites in East Africa as per the UKMO-HADCM3 GCM model for the SRES A1B scenario.

Growing season	Debre Zeit		Kabete		Ukiriguru	
	Baseline	Proj. 2050	Baseline	Proj. 2050	Baseline	Proj. 2050
Maximum temperature (°C)						
May–Sept	–	–	–	–	27.5–30.1	2.1–2.9
Jun–Oct	–	–	20.4–24.4	2.0–2.6	–	–
Oct–Feb	25.3–27.2	1.9–2.3	–	–	–	–
Minimum temperature (°C)						
May–Sept	–	–	–	–	14.8–17.4	2.8–3.0
Jun–Oct	–	–	9.9–12.1	2.9–3.1	–	–
Oct–Feb	8.4–11.0	2.8–3.4	–	–	–	–
Rainfall (mm) and % change						
May	–	–	–	–	76	−68
Jun	–	–	41	−34	10	0
Jul	–	–	19	16	6	−17
Aug	–	–	28	39	12	−8
Sept	–	–	27	70	26	46
Oct	22	9	64	−25	–	–
Nov	8	25	–	–	–	–
Dec	5	20	–	–	–	–
Jan	12	92	–	–	–	–
Feb	25	36	–	–	–	–

See Table 2 for explanation of abbreviations.

Table 4
Impact of climate change factors (temperature, CO_2 and rainfall) on seed yield (kg ha^{-1}) of chickpea at the selected sites in South Asia and East Africa during 2030 and 2050.

Year	Climate scenario	South Asia							
		Hisar		Indore		Nandhyal		Zaloke	
		Yield	% Ch.[a]	Yield	% Ch.	Yield	% Ch.	Yield	% Ch.
Baseline		1322		1813		1181		960	
2030	T	1390	5	1810	0	1001	−15	983	2
2030	T + CO_2	1528	16	1997	10	1136	−4	1074	12
2030	T + CO_2 + R	1414	7	2017	11	1135	−4	1065	11
2050	T	1440	9	1749	−4	794	−33	970	1
2050	T + CO_2	1698	28	2095	16	982	−17	1152	20
2050	T + CO_2 + R	1547	17	2115	17	994	−16	1134	18
LSD (0.05)[b]		60		35		30		21	

Year	Climate scenario	East Africa					
		Debre Zeit		Kabete		Ukiriguru	
		Yield	% Ch.	Yield	% Ch.	Yield	% Ch.
Baseline		1341		2031		1608	
2030	T	1386	3	2006	−1	1515	−6
2030	T + CO_2	1478	10	2221	9	1595	−1
2030	T + CO_2 + R	1521	13	2252	11	1605	0
2050	T	1404	5	1955	−4	1394	−13
2050	T + CO_2	1601	19	2343	15	1506	−6
2050	T + CO_2 + R	1674	25	2398	18	1503	−7
LSD (0.05)[b]		89		64		43	

T = Temperature; CO_2 = Carbon dioxide; R = Rainfall.
[a] Percent change in yield with respect to the baseline yield.
[b] Least significant difference at 5% level of probability to compare yields within the same column.

chickpea yields at the East Africa sites were statistically significant ($P < 0.05$) when compared with the respective baseline yields.

3.2. Chickpea response to genetic traits in South Asia

At Hisar the baseline cultivar RSG 888 took 95 days to 50% flowering and 153 days to physiological maturity and produced 1322 kg of seed yield per hectare when simulated with baseline climate (Table 5). The yields of 10% shorter and baseline cultivar were the same; however, for 10% longer maturity cultivars the yield decreased by 27%. This indicates that the current maturity duration of RSG 888 holds well for higher yields at Hisar. Combining yield potential traits with virtual cultivars resulted in 6% and 12% increase in yield of baseline and shorter maturity cultivars, respectively; whereas in case of longer maturity cultivar the yield decreased by 4%. Under climate change the shorter maturity cultivars had 10% higher yield over the baseline cultivar yield, which was statistically significant ($P < 0.05$); whereas the yield of longer maturity cultivar decreased by 41%. Under climate change, the contribution of yield potential traits to the yield of three maturity types was less when compared to that under the baseline climate. Incorporation of drought tolerance significantly ($P < 0.05$) increased the yield of virtual cultivars under both the climate regimes, giving 4–16% increase in yield under baseline climate and 10–14% under climate change (Table 6). The largest increase in yield was for the 10% shorter maturity cultivar both with and without yield potential traits. The yield gains due to heat tolerance for the virtual cultivars ranged from nil to 9% under baseline climate and nil to 6% under climate change. Larger yield gains due to heat tolerance ranging from 5 to 9% were expressed in the 10% longer maturity cultivars under both the climate regimes and these gains were statistically significant ($P < 0.05$). The combined benefit of drought and heat tolerance across virtual cultivars ranged from 14 to 16% under baseline climate and 11–20% under climate change.

At Indore the baseline cultivar Vijay took 56 days to 50% flowering and 118 days to physiological maturity and produced on average 1813 kg of seed yield per hectare under baseline climate (Table 5). As compared to the baseline cultivar, the 10% shorter maturity cultivar produced 4% higher yield and the 10% longer maturity cultivar produced 13% lower yield. Incorporating yield potential traits increased the yields by 1–6% across the three maturity duration cultivars with the highest benefit to the shorter maturity cultivar. Under climate change the 10% shorter maturity cultivar yielded the highest, whereas the longer maturity cultivar had 15% reduction in yield as compared to the baseline cultivar yield. Yield potential traits increased the yields by 3–6% for the three maturity cultivars. The yield benefit due to drought tolerance ranged from 19 to 22% under baseline climate and 14–20% under climate change with relatively greater benefit to virtual cultivars having high yielding potential traits (Table 6). As in the case of Hisar, larger benefits due to heat tolerance were associated with the low yielding longer maturity cultivars under both the climate regimes. In such cultivars the maximum yield gain was limited to 3% under baseline climate and 5% under climate change as compared to the baseline yields of their counterparts. These yield gains due to heat tolerance were statistically significant ($P < 0.05$). The yield gains due to the combination of drought and heat tolerance across virtual cultivars were more than their additive effects.

At Nandhyal the baseline cultivar JG 11 took 43 days to 50% flowering and 90 days to physiological maturity and produced on average 1181 kg of seed yield per hectare under baseline climate (Table 5). When compared to the baseline cultivar, the yield of 10% shorter maturity cultivar was significantly ($P < 0.05$) less by 7%, whereas the yield of 10% longer maturity cultivar increased by 2%. Incorporating yield potential traits increased chickpea yields by 4–7% across the three maturity duration cultivars. The highest yield (1260 kg ha^{-1}) was simulated with the 10% longer duration cultivar with yield potential traits. Under climate change, the yield benefits due to yield potential traits ranged from 4 to 11% across virtual cultivars. Yield benefit due to drought tolerance across virtual cultivars ranged from 12 to 16% under baseline climate and 8–11% under climate change and these gains were statistically significant ($P < 0.05$) over the baseline yields (Table 7). Incorporation of heat tolerance did not benefit the virtual cultivars under

Table 5
Seed yield (kg ha^{-1}) of chickpea virtual cultivars under both baseline climate and climate change (T + CO_2 + R) by 2050 at the selected sites in South Asia.

Virtual cultivars	Baseline climate				Climate change		
	FL	PM	Yield	% Change	Yield	% Change	LSD (0.05)[b]
Hisar							
Baseline	95	153	1322		1547		76
10% Shorter	85	138	1317	0	1705	10	49
10% Longer	105	170	969	−27	916	−41	96
Baseline + YP	95	152	1398	6[a]	1548	0[a]	93
10% shorter + YP	85	137	1471	12[a]	1836	8[a]	52
10% Longer + YP	105	168	929	−4[a]	853	−7[a]	107
LSD (0.05)[b]			92		56		
Indore							
Baseline	56	118	1813		2115		44
10% Shorter	50	106	1880	4	2230	5	36
10% Longer	62	130	1577	−13	1805	−15	48
Baseline + YP	56	117	1884	4[a]	2206	4[a]	47
10% shorter + YP	50	105	1988	6[a]	2354	6[a]	41
10% Longer + YP	62	129	1592	1[a]	1854	3[a]	50
LSD (0.05)[b]			33		41		
Nandhyal							
Baseline	43	90	1181		994		37
10% Shorter	39	82	1095	−7	883	−11	45
10% Longer	47	100	1210	2	991	0	27
Baseline + YP	43	90	1246	6[a]	1060	7[a]	36
10% shorter + YP	39	81	1172	7[a]	978	11[a]	45
10% Longer + YP	47	99	1260	4[a]	1030	4[a]	27
LSD (0.05)[b]			20		30		
Zaloke							
Baseline	47	96	960		1134		27
10% Shorter	42	86	975	2	1129	0	25
10% Longer	52	106	1021	6	1217	7	31
Baseline + YP	47	95	990	3[a]	1173	3[a]	32
10% shorter + YP	42	86	1020	5[a]	1176	4[a]	31
10% Longer + YP	52	106	1076	5[a]	1271	4[a]	35
LSD (0.05)[b]			37		34		

YP: Yield potential; FL: Days to 50% Flowering; PM: Days to physiological maturity; % Change: Percent change in yield due to crop maturity or yield potential traits.
[a] Yield improvement compared to the cultivar with same crop maturity.
[b] Least significant difference at 5% level of probability to compare yields within the same row or column.

Table 6
Effect of incorporating drought and heat tolerance traits on the mean seed yield (kg ha^{-1}) of virtual cultivars at the Hisar and Indore sites in South Asia.

Virtual cultivars	Baseline yield	Drought tolerance		Heat tolerance		Drought + heat tolerance		LSD (0.05)[a]
		Yield	% Change	Yield	% Change	Yield	% Change	
Hisar-Baseline climate								
Baseline	1322	1472	11	1339	1	1533	16	27
10% Shorter	1317	1504	14	1318	0	1499	14	31
10% Longer	969	1011	4	1055	9	1122	16	22
Baseline + YP	1398	1560	12	1432	2	1623	16	34
10% shorter + YP	1471	1713	16	1472	0	1709	16	34
10% Longer + YP	929	983	6	1006	8	1078	16	26
Hisar-Climate 2050								
Baseline	1547	1697	10	1595	3	1769	14	27
10% Shorter	1705	1925	13	1697	0	1895	11	36
10% Longer	916	1005	10	973	6	1077	18	21
Baseline + YP	1548	1724	11	1609	4	1802	16	30
10% shorter + YP	1836	2100	14	1833	0	2095	14	34
10% Longer + YP	853	966	13	899	5	1027	20	26
Indore-Baseline climate								
Baseline	1813	2173	20	1820	0	2203	21	22
10% Shorter	1880	2236	19	1874	0	2235	19	25
10% Longer	1577	1871	19	1625	3	1953	24	24
Baseline + YP	1884	2284	21	1893	0	2309	23	29
10% shorter + YP	1988	2435	22	1996	0	2465	24	23
10% Longer + YP	1592	1936	22	1646	3	2027	27	27
Indore-Climate 2050								
Baseline	2115	2475	17	2148	2	2578	22	35
10% Shorter	2230	2550	14	2229	0	2555	15	47
10% Longer	1805	2117	17	1896	5	2285	27	29
Baseline + YP	2206	2646	20	2236	1	2732	24	37
10% shorter + YP	2354	2806	19	2345	0	2843	21	33
10% Longer + YP	1854	2227	20	1946	5	2394	29	32

YP: Yield potential; % Change: Percent yield gain due to the trait compared to the baseline yield of a virtual cultivar with the same crop maturity and yield potential traits.
[a] Least significant difference at 5% level of probability to compare yields within the same row.

Table 7
Effect of incorporating drought and heat tolerance traits on the mean seed yield (kg ha^{-1}) of virtual cultivars at the Nandhyal and Zaloke sites in South Asia.

Virtual cultivars	Baseline yield	Drought tolerance		Heat tolerance		Drought + heattolerance		LSD (0.05)[a]
		Yield	% Change	Yield	% Change	Yield	% Change	
Nandhyal-Baseline climate								
Baseline	1181	1358	15	1122	−5	1293	9	15
10% Shorter	1095	1270	16	1039	−5	1209	10	20
10% Longer	1210	1361	12	1160	−4	1307	8	14
Baseline + YP	1246	1423	14	1185	−5	1358	9	19
10% shorter + YP	1172	1360	16	1113	−5	1291	10	18
10% Longer + YP	1260	1408	12	1210	−4	1355	8	17
Nandhyal-Climate 2050								
Baseline	994	1092	10	1048	5	1188	20	35
10% Shorter	883	961	9	1002	13	1156	31	45
10% Longer	991	1071	8	1024	3	1137	15	23
Baseline + YP	1060	1171	10	1096	3	1239	17	32
10% shorter + YP	978	1082	11	1059	8	1225	25	46
10% Longer + YP	1030	1116	8	1055	2	1169	14	22
Zaloke-Baseline climate								
Baseline	960	1134	18	955	−1	1126	17	23
10% Shorter	975	1181	21	969	−1	1174	20	25
10% Longer	1021	1215	19	1010	−1	1207	18	21
Baseline + YP	990	1165	18	983	−1	1157	17	30
10% shorter + YP	1020	1228	20	1016	0	1222	20	29
10% Longer + YP	1076	1275	18	1064	−1	1262	17	26
Zaloke-Climate 2050								
Baseline	1134	1350	19	1111	−2	1320	16	29
10% Shorter	1129	1344	19	1118	−1	1332	18	27
10% Longer	1217	1395	15	1195	−2	1386	14	35
Baseline + YP	1173	1401	19	1146	−2	1362	16	33
10% shorter + YP	1176	1393	18	1168	−1	1381	17	31
10% Longer + YP	1271	1441	13	1251	−2	1436	13	40

See Table 6 for explanation of abbreviations and superscripts.

baseline climate; however, under climate change the yields increased by 2–13% across virtual cultivars, which was a significant ($P < 0.05$) increase over the baseline yields.

At Zaloke the baseline cultivar JG 11 took six more days to reach physiological maturity than at Nandhyal (Table 5). Among the three virtual cultivars, the 10% longer maturity virtual cultivar produced the maximum yield, which was 6% more than the yield of the baseline cultivar. Enhanced yield potential traits increase the yield of virtual cultivars by 3–5% under the baseline climate. Under climate change, the 10% longer maturity cultivar, with or without yield potential traits, produced a significantly higher yield ($P < 0.05$) than the baseline cultivar. The yield gain of virtual cultivars due to yield potential traits was up to 4% under climate change. These results showed that under baseline and future climates at Zaloke a longer maturity cultivar than the baseline cultivar will give higher yields. The yield benefits due to drought tolerance across virtual cultivars ranged from 18 to 21% under baseline climate and 13–19% under climate change (Table 7). Incorporation of heat tolerance had insignificant effect on the yield of virtual cultivars under both the baseline and climate change scenarios.

3.3. Chickpea response to genetic traits in East Africa

At Debre Zeit the baseline cultivar JG 11 took 108 days to physiological maturity and produced 1341 kg seed yield per hectare (Table 8). Under baseline climate, the maximum yield (1483 kg ha^{-1}) was simulated with the 10% shorter maturity cultivar, which was a significant ($P < 0.05$) yield increase over the baseline cultivar. The yield of 10% longer maturity cultivar was 18% less (1099 kg ha^{-1}) than the yield of baseline cultivar. Under both the climate regimes, incorporation of yield potential traits resulted in higher yield gains (5–6%) only when placed in the 10% shorter maturity cultivar. Under climate change, the relative performance of virtual cultivars was the same as under baseline climate. Yield benefit due to drought tolerance across virtual cultivars ranged from 4 to 15% under baseline climate and 8–14% under climate change (Table 9). Except for the longer maturity cultivars under baseline climate, these yield gains were statistically significant ($P < 0.05$). The maximum yield benefit due to drought tolerance was with the 10% shorter maturity cultivar, both with and without high yield potential traits, under both the climatic regimes. Incorporation of heat tolerance had no effect on the yields of virtual cultivars under both the climate regimes at this site.

At Kabete the baseline cultivar JG 11 took 96 days to physiological maturity and produced 2031 kg seed yield per hectare (Table 8). Under baseline climate the best yields were simulated with the baseline cultivar compared to shorter or longer cycle cultivars. Yield potential traits increased the yields of virtual cultivars from nil to 6% and the maximum increase was with the shorter maturity cultivar. Under climate change, the baseline cultivar, with or without yield potential traits had higher yield than shorter or longer cycle cultivars. The yield of the 10% longer maturity cultivars was significantly ($P < 0.05$) lower than the yield of other cultivars under both the climate regimes. The yield benefit due to yield potential traits was up to 6% for the virtual cultivars under climate change (Table 8). Incorporation of drought tolerance increased the yield of virtual cultivars by 10–19% under baseline climate and 11–16% under climate change (Table 9). The maximum yield increases due to this trait were mostly associated with the 10% shorter maturity cultivars. The effect of heat tolerance on yield of cultivars was statistically non-significant ($P < 0.05$) under both the climate regimes.

Ukiriguru in Tanzania is the warmest and the highest rainfall site compared to the other two sites studied in the East Africa. The baseline cultivar matured in 89 days at this site and produced 1608 kg seed yield per hectare (Table 8). The yields of the baseline and 10% shorter maturity cultivars did not differ significantly ($P < 0.05$). The yield of the 10% longer maturity cultivar was significantly ($P < 0.05$) lower than the yield of the baseline or the shorter maturity cultivar. Under climate change, the yields of baseline and 10% longer maturity virtual cultivars decreased, but in case of 10%

Table 8
Seed yield (kg ha^{-1}) of chickpea virtual cultivars under both baseline climate and climate change (T + CO_2 + R) by 2050 at the selected sites in East Africa.

Virtual cultivars	Baseline climate				Climate change		
	FL	PM	Yield	% Change	Yield	% Change	LSD (0.05)[b]
Debre Zeit							
Baseline	55	108	1341		1674		114
10% Shorter	50	99	1483	11	1896	13	110
10% Longer	60	118	1099	−18	1325	−21	114
Baseline + YP	55	107	1329	−1[a]	1701	2[a]	136
10% shorter + YP	50	98	1569	6[a]	1998	5[a]	126
10% Longer + YP	60	117	1084	−1[a]	1319	0[a]	134
LSD (0.05)[b]			133		92		
Kabate							
Baseline	48	96	2031		2398		81
10% Shorter	43	88	1910	−6	2330	−3	48
10% Longer	52	105	1743	−14	2087	−13	113
Baseline + YP	48	96	2116	4[a]	2480	3[a]	95
10% shorter + YP	43	87	2026	6[a]	2460	6[a]	58
10% Longer + YP	52	104	1736	0[a]	2111	1[a]	135
LSD (0.05)[b]			110		185		
Ukiriguru							
Baseline	43	89	1608		1503		51
10% Shorter	39	80	1624	1	1778	18	45
10% Longer	47	96	1325	−18	1119	−26	46
Baseline + YP	43	88	1612	0[a]	1458	−3[a]	48
10% shorter + YP	39	80	1687	4[a]	1790	1[a]	48
10% Longer + YP	47	95	1283	−3[a]	1053	−6[a]	51
LSD (0.05)[b]			82		89		

See Table 5 for explanation of abbreviations and superscripts.

shorter maturity cultivars it significantly ($P < 0.05$) increased. The yield benefits due to yield potential traits at this site were statistically non-significant ($P < 0.05$) under both the climate regimes. Ukiriguru being a warmer and high rainfall site, the yield benefits due to drought tolerance traits were the lowest among all the sites considered in this study (Table 10). The maximum yield increase due this trait was up to 13% under baseline climate and up to 7% under climate change, and the significant ($P < 0.05$) yield gains were mostly associated with the shorter maturity virtual cultivars when compared to the baseline yields. The yield benefit due to heat tolerance across virtual cultivars was negligible under baseline climate. However under climate change, the yields for the baseline cultivars increased up to 4%, which were statistically significant ($P < 0.05$) when compared to the baseline yields (Table 10).

Table 9
Effect of incorporating drought and heat tolerance traits on the mean seed yield (kg ha^{-1}) of virtual cultivars at the Debra Zeit and Kabete sites in East Africa.

Virtual cultivar	Baseline yield	Drought tolerance		Heat tolerance		Drought + heat tolerance		LSD (0.05)[a]
		Yield	% Change	Yield	% Change	Yield	% Change	
Debre Zeit-Baseline climate								
Baseline	1341	1452	8	1344	0	1456	9	51
10% Shorter	1483	1708	15	1480	0	1708	15	44
10% Longer	1099	1152	5	1098	0	1151	5	57
Baseline + YP	1329	1428	7	1330	0	1431	8	71
10% shorter + YP	1569	1784	14	1569	0	1786	14	58
10% Longer + YP	1084	1131	4	1083	0	1130	4	60
Debre Zeit-Climate 2050								
Baseline	1674	1829	9	1683	1	1849	10	68
10% Shorter	1896	2170	14	1889	0	2170	14	53
10% Longer	1325	1429	8	1330	0	1438	9	81
Baseline + YP	1701	1867	10	1711	1	1881	11	92
10% shorter + YP	1998	2283	14	1992	0	2287	15	71
10% Longer + YP	1319	1438	9	1324	0	1449	10	101
Kabete-Baseline climate								
Baseline	2031	2309	14	2034	0	2320	14	34
10% Shorter	1910	2243	17	1908	0	2241	17	49
10% Longer	1743	1914	10	1751	0	1933	11	44
Baseline + YP	2116	2414	14	2116	0	2420	14	59
10% shorter + YP	2026	2401	19	2019	0	2396	18	38
10% Longer + YP	1736	1935	11	1745	1	1948	12	65
Kabete-Climate 2050								
Baseline	2398	2681	12	2418	1	2741	14	58
10% Shorter	2330	2614	12	2298	−1	2620	12	101
10% Longer	2087	2315	11	2141	3	2390	14	63
Baseline + YP	2480	2809	13	2501	1	2853	15	68
10% shorter + YP	2460	2857	16	2427	−1	2839	15	72
10% Longer + YP	2111	2384	13	2148	2	2436	15	64

See Table 6 for explanation of abbreviations and superscripts.

Table 10
Effect of incorporating drought and heat tolerance traits on the mean seed yield (kg ha^{-1}) of virtual cultivars at the Ukiriguru site in East Africa.

	Baseline yield	Drought tolerance		Heat tolerance		Drought + heat tolerance		LSD (0.05)[a]
		Yield	% Change	Yield	% Change	Yield	% Change	
Ukiriguru-Baseline climate								
Baseline	1608	1699	6	1616	0	1724	7	19
10% Shorter	1624	1828	13	1600	−2	1802	11	15
10% Longer	1325	1337	1	1339	1	1358	2	24
Baseline + YP	1612	1664	3	1629	1	1698	5	20
10% shorter + YP	1687	1882	12	1646	−2	1843	9	16
10% Longer + YP	1283	1279	0	1293	1	1291	1	24
Ukiriguru-Climate 2050								
Baseline	1503	1513	1	1558	4	1582	5	24
10% Shorter	1778	1897	7	1779	0	1945	9	31
10% Longer	1119	1086	−3	1132	1	1110	−1	21
Baseline + YP	1458	1459	0	1508	3	1517	4	25
10% shorter + YP	1790	1882	5	1816	1	1958	9	33
10% Longer + YP	1053	1028	−2	1062	1	1036	−2	23

See Table 6 for explanation of abbreviations and superscripts.

4. Discussion

Using the CROPGRO-Chickpea model, we have quantified the impact of climate change on chickpea yields at the selected sites in South Asia and East Africa. We have also evaluated the impact of crop life-cycle duration, yield potential, drought and heat tolerance traits and their combinations on chickpea yield under baseline and future climates of the sites. Climate change (T + CO_2 + R) by 2050 increased the yield of chickpea by 17–25% at the cooler sites (Hisar, Indore, Zaloke, Debre Zeit and Kabete) but decreased the yield by 7–16% at the warmer sites (Nandhyal and Ukiriguru). The increase in yield at the cooler sites is primarily attributed to favorable warmer temperatures due to climate change and increased atmospheric CO_2 concentration that promoted crop growth, pod and seed setting in chickpea. Poor pod and seed setting in chickpea under low temperatures has been reported by several researchers (Croser et al., 2003; Clarke and Siddique, 2004) and attempts are being made to breed cold tolerant varieties. Increase in yield of rainfed chickpea under climate change has also been reported by Koocheki et al. (2006) for the Tabriz area in Iran and for selected sites in Iran and Syria by Gholipoor and Soltani (2009). Although climate change to some degree in future will overcome the problem of low temperatures affecting yields at the sites, the occurrence of drought stress would still remain a constraints to realize high yields. Additionally at some cooler sites (Hisar and Indore), heat stress especially during pod-filling close to maturity would also affect yields in some years. Yield reduction at currently warmer sites (Nandhyal and Ukiriguru) is attributed to increased heat or drought stress or both with climate change limiting growth and yield formation in chickpea.

Simulations showed that longer life cycle cultivars gave lower yields than standard life cycle cultivars at a number of sites (Hisar, Indore, Debre Zeit, Kabete and Ukiriguru) under either baseline or future climate because the longer cycle exposed the crop to warmer temperatures later in the season along with soil water depletion during the critical grain-set and grain-filling phase. Chickpea is grown on stored water, so longer life cycle can potentially be a problem if the water is depleted before grain-filling is completed. Under baseline climate at some sites, either shorter (Indore, Debre Zeit Ukiriguru) or longer (Nandhyal and Zaloke) cycle cultivars than the baseline cultivar were needed for achieving maximum yield. Under climate change, except for Hisar, the optimum life cycle duration for highest yields at the sites was associated with the same maturity durations as under the baseline climate. At Hisar, the increase in temperature with climate change was more favorable for chickpea growth, but shorter duration cultivars were required for higher yields to escape drought during reproductive growth. The simulation results showed that under both current and future climates, fitting crop life cycle to the rainfall and temperature regimes of the sites will be a valuable adaptation process and sufficient genetic variability exists in the maturity traits among chickpea genotypes (Pundir et al., 1988).

Enhanced yield potential traits (maximum leaf photosynthesis rate, maximum fraction of daily growth partitioned to pods and seed-filling duration for pod cohort each increased by 10%) increased yield at all the sites. Under baseline climate, the yield potential traits increased the yield of virtual cultivars up to 7% across the selected sites, except at Hisar where larger increase in yield up to 12% was simulated by combining yield potential traits with the shorter maturity cultivar. These yield gains for chickpea are less than those simulated for groundnut (9–14%) with the same yield enhancing traits (Singh et al., 2012). Under climate change the contribution of yield potential traits to yield was less at some sites, possibly due to greater heat and water stress on photosynthesis, partitioning, and seed filling duration. The lesser response to yield potential traits under long life cycles can be explained in some cases, because the greater photosynthesis along with longer cycle should give higher leaf area index, which can be a negative factor if it accelerates water depletion prior to the end of grain-filling.

The benefits of incorporating drought tolerance in chickpea were variable and depended upon the maturity duration of the baseline cultivars and the prevailing temperature and rainfall regimes of the crop growing season at the selected sites. Across sites and virtual cultivars, the yield increase due to drought tolerance ranged from nil to 22% under baseline climate and nil to 20% under climate change. Yield gains due to drought tolerance were the highest at Indore followed by Zaloke under both baseline climate and climate change. This is attributed to low rainfall and moderate temperatures during the growing season at these two sites. Vadez et al. (2012) reported 8–12% increase in yield of chickpea with root-related traits that promoted greater soil water use by the crop by increasing the depth of effective water extraction. Their study confirms the model simulations of drought tolerance traits, although specific differences in yield gain could be attributed to different environments experienced (weather and soil), as well as the approach adopted in the model for quantifying the benefits due to drought tolerance. Vadez et al. (2012) in their approach achieved greater water use by the drought tolerant chickpea by increasing maximum depth of soil water extraction, whereas in our study we promoted greater mining of water from the soil with increased root length density without increasing soil depth. Though drought tolerance in chickpea may be attributed to many plant traits, increased root length density at deeper zones in the soil profile resulting in greater water extraction during the period of

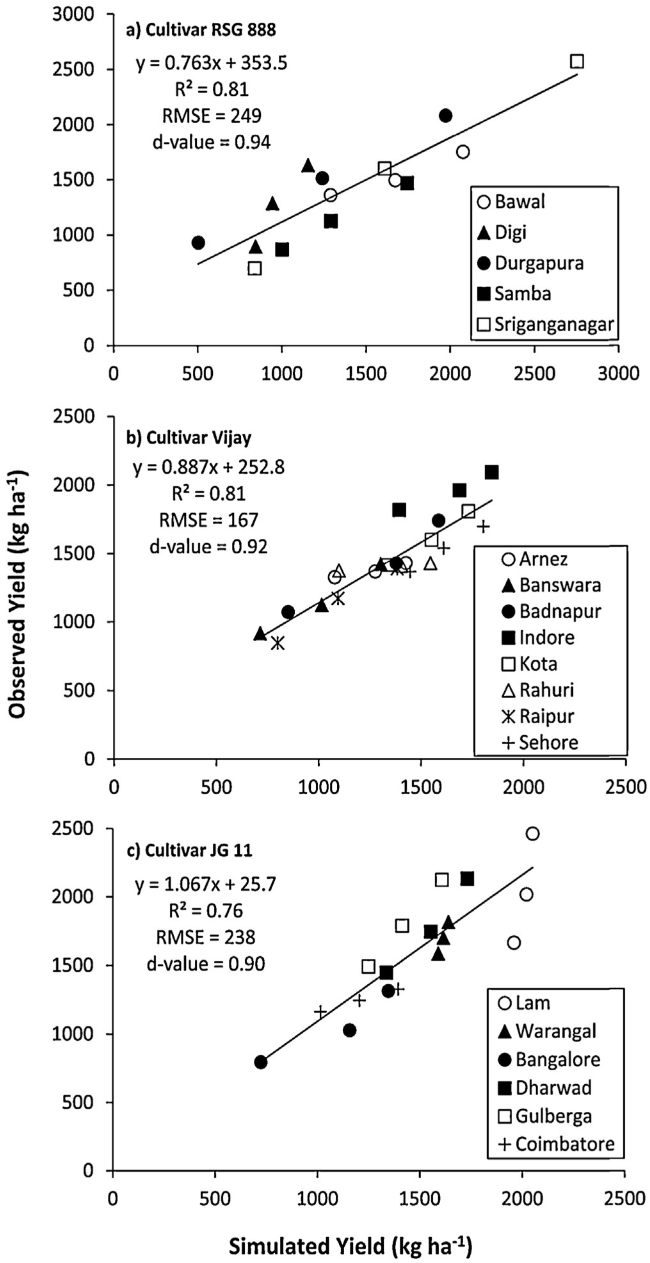

Fig. 3. Relationship of simulated seed yield with the observed yield across sites in India for cultivars (a) RSG 888, (b) Vijay and (c) JG 11.

water deficit is the likely mechanism of drought tolerance for higher yields. Better root length density and its distribution in the soil profile have been related to higher yields in chickpea under drought stress (Kashiwagi et al., 2005, 2006) and genetic variation in rooting traits has been identified in chickpea and is being used to breed drought tolerant chickpea cultivars (Serraj et al., 2004; Gaur et al., 2008; Krishnamurthy et al., 2010). Thus the approach used in the model to simulate the benefits of drought tolerance is appropriate.

Yield gains due to the heat tolerance trait were predicted only for the Hisar and Indore sites under the baseline climate. These gains were up to 9% increase in yield and were associated with the longer cycle cultivars which exposed the crop to warmer late season temperatures. For other sites incorporation of the heat tolerance trait had no beneficial effect on seed yield under baseline climate. Under climate change, yield gains due to heat tolerance were simulated for the Hisar (up to 6%), Indore (up to 5%), Nandhyal (up to 13%) and Ukiriguru (up to 4%) sites and were associated with cultivars of varying maturity durations. At some sites and climate regimes (for example, Nandhyal under baseline climate) the yield of chickpea was less with the heat tolerance traits incorporated. This could be attributed to faster crop senescence with increased sink demand for assimilates with heat tolerance, thus not being able to fill seeds especially under water-limiting situations. The cultivar response to the heat tolerance traits under baseline and climate change is primarily determined by the current temperature regimes of the sites and water availability to the crop, due to rainfall and soil water retention properties of the soils affecting total biomass production by the crop. The yield benefits due to heat tolerance simulated in this study are also realistic as the mechanisms for yield losses due to high temperature stress in the chickpea model are similar for most legumes as reported by Prasad et al. (1999, 2002), Boote et al. (2005), and Wang et al. (2006). Large variation in heat tolerance among chickpea genotypes under field conditions in India has been reported by Krishnamurthy et al. (2011) and Dua (2001) and in controlled environment studies by Devasirvatham et al. (2012a, 2012b). Thus it should be possible to breed heat tolerant chickpea cultivars to suit the current and future warmer growing conditions of the selected sites.

The study revealed that the prioritization of plant traits to breed new chickpea cultivars for higher yields under climate change will vary with the selected sites (Table 11). At Indore and Zaloke drought tolerance is the priority trait for increasing yields; whereas at Nandhyal both heat tolerance and yield potential are the priority traits. At Zaloke and Debre Zeit, heat tolerance is not a priority trait under climate change as compared to drought tolerance or yield potential trait. At Ukiriguru adjusting the crop life cycle will be sufficient to increase the yield of chickpea; whereas at Kabete the use of baseline cultivar with some degree of drought tolerance will be required for higher yields. At Hisar, a short duration cultivar along with some degree of drought and heat tolerance and yield potential traits will be needed to increase yields under climate change.

Table 11
Yield of baseline cultivar under climate change by 2050 and percentage gain or loss in yield by incorporating short duration (SD), long duration (LD), yield potential (YP), drought tolerance (DT) and heat tolerance (HT) traits in virtual cultivars at the selected sites in South Asia and East Africa.

Site	Baseline cultivar (kg ha^{-1})	SD	LD	YP[a]	DT[a]	HT[a]
		Yield gain or loss (%)				
Hisar	1547	10	−41	8	10–14	3–6
Indore	2115	5	−15	3–6	14–20	5
Nandhyal	994	−11	0	4–11	8–11	2–13
Zaloke	1134	0	7	3–4	13–19	–
Debre Zeit	1674	13	−21	5	8–14	–
Kabete	2398	−3	−13	–	11–16	–
Ukiriguru	1503	18	−26	–	5–7	3–4

[a] Only the statistically significant ($P < 0.05$) gains in yield due to YP, DT and HT of virtual cultivars are presented.

5. Conclusions

Climate change by 2050 increased the yield of chickpea by 17–25% at the cooler sites (Hisar, Indore, Zaloke, Debre Zeit, and Kabete) and decreased yield by 7–16% at the warmer sites (Nandhyal and Ukiriguru) as compared to the yields under baseline climate of the sites. The life cycle duration of cultivars for obtaining higher yields was determined by the temperature and rainfall regimes of the sites in future. Yield was less for longer life cycle cultivars at a number of sites (Hisar, Indore, Debre Zeit, Kabete and Ukiriguru) because longer cycle exposed the crop to warmer temperatures as well as soil water depletion later in the season. Across climate regimes, the yield potential traits increased the yield of virtual cultivars up to 12% and with drought tolerance up to 22% as compared to the yield of cultivars without these traits. Heat tolerance increased the yields up to 9% at Hisar and Indore under the baseline climate and up to 13% at Nandhyal, Hisar, Indore and Ukiriguru under climate change. At other sites (Zaloke, Debre Zeit and Kabete) incorporation of heat tolerance had no beneficial effect on yield under climate change. Considering varied crop responses to plant traits across sites, this study was useful in prioritizing plant traits for location-specific breeding of new chickpea cultivars and selection by farmers for higher yields under climate change at the selected sites in South Asia and East Africa. These results can also be extended to other sites in these regions with similar climatic and edaphic conditions.

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