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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,

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* 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