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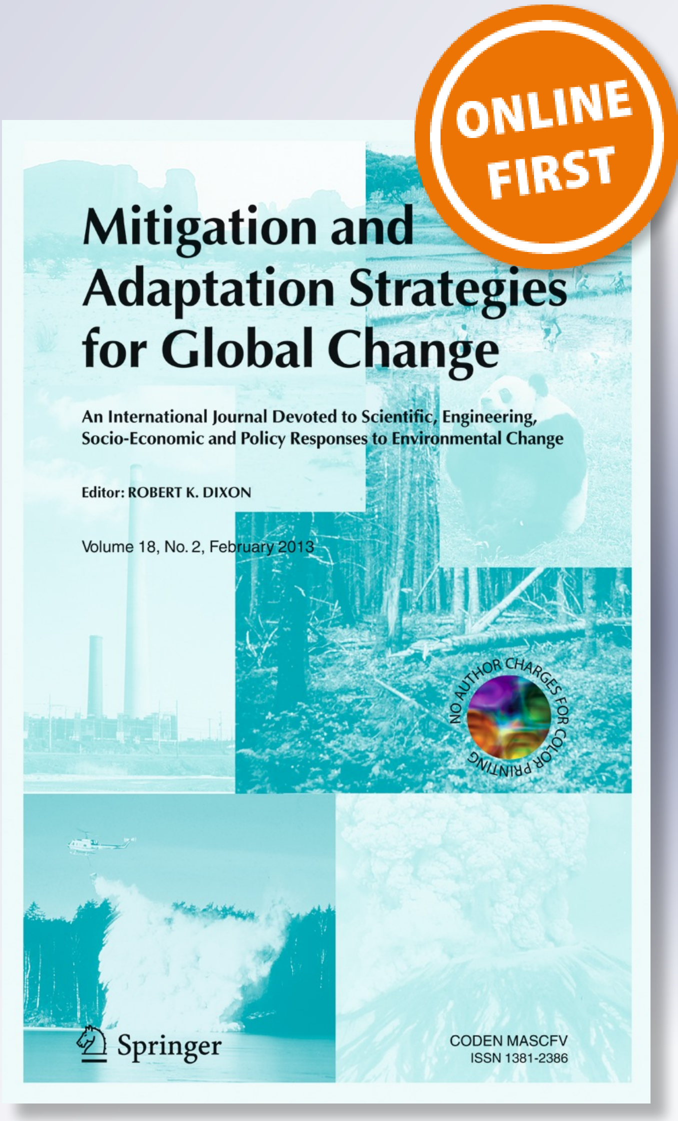

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ORIGINAL ARTICLE

Potential benefits of drought and heat tolerance in groundnut for adaptation to climate change in India and West Africa

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Abstract Climate change is projected to intensify drought and heat stress in groundnut (*Arachis hypogaea* L.) crop in rainfed regions. This will require developing high yielding groundnut cultivars that are both drought and heat tolerant. The crop growth simulation model for groundnut (CROPGRO-Groundnut model) was used to quantify the potential benefits of incorporating drought and heat tolerance and yield-enhancing traits into the commonly grown cultivar types at two sites each in India (Anantapur and Junagadh) and West Africa (Samanko, Mali and Sadore, Niger). Increasing crop maturity by 10 % increased yields up to 14 % at Anantapur, 19 % at Samanko and sustained the yields at Sadore. However at Junagadh, the current maturity of the cultivar holds well under future climate. Increasing yield potential of the crop by increasing leaf photosynthesis rate, partitioning to pods and seed-filling duration each by 10 % increased pod yield by 9 to 14 % over the baseline yields across the four sites. Under current climates of Anantapur, Junagadh and Sadore, the yield gains were larger by incorporating drought tolerance than heat tolerance. Under climate change the yield gains from incorporating both drought and heat tolerance increased to 13 % at Anantapur, 12 % at Junagadh and 31 % at Sadore. At the Samanko site, the yield gains from drought or heat tolerance were negligible. It is concluded that different combination of traits will be needed to increase and sustain the productivity of groundnut under climate change at the target sites and the CROPGRO-Groundnut model can be used for evaluating such traits.

Keywords Climate change factors · Genetic improvement · Heat and drought tolerance · Peanut · CROPGRO-Peanut model

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1 Introduction

According to The United Nations Intergovernmental Panel on Climate Change (IPCC) (2007), increased concentration of greenhouse gases in the atmosphere is warming the globe, which is causing climate change in terms of higher temperatures, changing patterns of precipitation and water availability and increased frequency of extreme weather events such as floods, storms and droughts. Depending upon the location on the globe, crop yields will be either negatively or positively affected by climate change. However, in the arid and semi-arid tropical (SAT) regions the effect of climate change is predicted to be mostly negative, thus threatening food security in these regions (Easterling 1996; Fischer et al. 2005; Howden et al. 2007). In the SAT regions, the changes in rainfall coupled with rise in temperature may reduce the length of growing period (Cooper et al. 2009). Increasing temperatures affect growth and development of crops, thus influencing potential yields. A critical variable is the number of days a crop is exposed to supra-optimal temperatures at critical growth stages, i.e., flowering, pollination or grain filling (Prasad et al. 2003). Free air carbon enrichment (FACE) experiments showed that crop productivity could increase in the range of 15–25 % for C3 crops like wheat (*Triticum aestivum*), rice (*Oryza sativa*) and soybean (*Glycine max*) and 5–10 % for C4 crops like maize (*Zea mays*), sorghum (*Sorghum bicolor*) and sugarcane (*Saccharum officinarum*) with the increase in atmospheric carbon dioxide (CO_2) concentration (Tubiello et al. 2007). Higher levels of CO_2 also improve water use efficiency of both C3 and C4 plants. 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 suit the characteristics of the future climate and other natural endowments of each area.

Groundnut (*Arachis hypogaea* L.) is an important food and oilseed crop grown by small and marginal farmers under diverse agro-climatic environments of India and West Africa. In India, it is grown largely (83 % of total groundnut area) under rainfed conditions during the main rainy season (Jun/Jul–Oct/Nov) and the remaining 17 % is irrigated mainly in the post-rainy (Oct–Mar) season. While India has the largest area under groundnut (6.36 million ha) in the world, its production (6.5 million tons) and productivity (1,022 $kg\,ha^{-1}$) have remained low; the latter being well below the world average (Birthal et al. 2010). In West Africa, although Nigeria and Senegal are the largest producers of groundnut, Mali and Niger are also important groundnut producers. In Mali groundnut is grown on 0.29 million ha with an average production and productivity of 0.26 million tones and 880 $kg\,ha^{-1}$, respectively. In Niger, groundnut is grown on a larger area (0.44 million ha) than in Mali, but with greater fluctuation in production due to variable climate. Average production and productivity of groundnut in Niger is 0.21 million tons and 480 $kg\,ha^{-1}$ (mean of 2001 to 2010 production data reported in FAO 2012). In West Africa, groundnut is usually sown between mid-June and mid-July. There are many region-specific abiotic and biotic stresses that limit groundnut productivity in India and Africa; however, drought and heat stress are the major yield limiting factors (Vara Prasad et al. 2009). Temperature regimes of these regions during the groundnut growing period are already close to or above the upper limit of the optimum temperature range (20–30 °C) required for groundnut. The projected climate changes for these regions in the near future will further intensify the problems of heat and drought stress in groundnut, thus further limiting its production potential. As climate change may reduce the length of growing period in the SAT regions (Cooper et al. 2009), it will be important to match the maturity duration of groundnut cultivars to the period of soil water availability for higher and stable yields. When climate changes are relatively small, current agronomic techniques can help farmers adapt. The early-stage agronomic adaptation measures include changing sowing dates and cultivars, fertilization, irrigation scheduling and switching to better-adapted alternative crops or increasing crop diversity (Aggarwal 2008; Easterling 1996; Howden et al. 2007). As climate change becomes more intense, more extensive changes may be needed including the 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 (Boote et al. 2011).

Plant breeders are already targeting specific plant traits to breed new crop varieties that will perform better under climate change. Therefore, it is imperative to make an early assessment of the potential benefits of such technologies 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 environments by using environment-specific weather, soil and agronomic management data (Boote et al. 2001, 2003). Since these models incorporate parameters representing genetic traits of cultivars, they 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; Singh et al. 2012). Using crop models, many researchers in the past have proposed genetic improvement of crops for higher yields (Landivar et al. 1983; Boote and Jones 1986; Whisler et al. 1986; Boote and Tollenaar 1994; Hammer et al. 1996, 2002, 2004, 2005; Yin et al. 1999; Boote et al. 2001, 2003; Tardieu 2003; White and Hoogenboom 2003; Messina et al. 2006; Suriharn et al. 2011). With improved knowledge and understanding of crop response to climate change factors (high temperatures, increased rainfall variability, increased atmospheric CO_2 concentration and their interactions) the crop models have excellent potential to assess the benefits of genetic improvement of crops under both current and future climates of the target sites.

The objective of this study was to quantify the potential benefits of genetic improvement, particularly crop maturity duration, yield potential, drought and heat tolerance traits and their combinations, on the yield of groundnut in current and future climates of selected sites in India and West Africa.

2 Materials and methods

2.1 Study sites

Simulations of groundnut crop were carried out for Anantapur and Junagadh sites in India and Samanko (Mali) and Sadore (Niger) sites in West Africa. Anantapur is a relatively drier site than the Junagadh site, both representing regions where groundnut is dominantly grown in India. Mean seasonal rainfall (June to October) is 455 mm at Anantapur and 724 mm at Junagadh (Table 1). Mean maximum and minimum temperatures during the season are 33.2 °C and 23.3 °C at Anantapur and 33.2 °C and 24.7 °C at Junagadh, respectively. The soil is an Alfisol (a low water holding capacity soil) at Anantapur and an Inceptisol (a high water holding capacity soil) at Junagadh. In West Africa, Samanko (Mali) is a wetter site with a seasonal rainfall (June to October) of 1,015 mm; whereas Sadore (Niger) is a drier site with seasonal rainfall (June to October) of 512 mm. Among the four sites, Samanko is the coolest site during the season with mean maximum and minimum temperatures of 30.0 and 22.4 °C, respectively; whereas Sadore is the hottest site with mean maximum and minimum temperatures of 35.3 and 23.6 °C, respectively. The soil is a medium water holding capacity Oxisol at Samanko and a low water holding capacity Peleustalf at Sadore (Table 1). Monthly values of baseline and projected changes in climate for the four sites are given in Table 2.

Table 1 Geographical, soil and climatic characteristics of the India and West Africa study sites

	India		West Africa	
	Anantapur	Junagadh	Samanko	Sadore
	Geographical characteristics			
Latitude (deg.)	14.68	21.31	12.53	13.25
Longitude (deg.)	77.62	70.36	−8.07	2.30
Elevation (m)	420	228	330	300
	Soil characteristics			
Soil type	Alfisol	Inceptisol	Oxisol (Latosol)	Psammentic paleustalf
Soil depth (cm)	90	165	155	90
EWHC (mm)	95	200	126	74
	Growing season climate (June to October)			
Mean max. temperature (°C)	33.2	33.3	30.9	35.3
Mean min. temperature (°C)	23.3	24.7	22.4	23.6
Mean temperature (°C)	28.3	29.0	26.6	29.5
Growing season rainfall (mm)	455	724	1015	512
PET (mm)	765	815	720	855

EWHC Extractable water holding capacity of soil, *PET* Potential evapotranspiration

The baseline groundnut cultivars used in the simulation analysis were JL 24 for Anantapur, M 335 for Junagadh, and 55–437 for Samanko and Sadore, representing the dominant cultivar types grown in the respective region. JL 24 is a Spanish type cultivar and takes about 100 to 105 days to mature. M 335 is Virginia Type cultivar and takes about 120 to 125 days to mature. Cultivar 55–437 is a Spanish type and takes about 95 to 100 days to mature.

2.2 The model

We used the CROPGRO-Groundnut model to evaluate genetic traits of groundnut for increasing its productivity under both current and future climates of the target sites. The groundnut model is part of the suit 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 (Boote et al. 1998). It simulates groundnut 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 temperature, precipitation and solar radiation and include the effect of soil characteristics on water availability for crop growth. Soil water balance is a function of precipitation, irrigation, runoff from the soil surface, soil evaporation, transpiration and drainage from the bottom of the soil profile. Daily surface runoff of water is calculated using the U.S. Department of Agriculture (USDA), Soil Conservation Service curve number technique (Soil Conservation Service 1972). For computing soil water drainage, the model uses a 'tipping bucket' approach when a layer's water content is above a drained upper limit (DUL). Upward unsaturated flow is also computed using a conservative estimate of the soil water diffusivity and differences in volumetric soil water content of

Table 2 Baseline and projected increase in maximum and minimum monthly temperatures and percent change in monthly rainfall by 2050 at the target sites as per the UKMO-HADCM3 GCM model for the SRES A1B scenario

Month	Anantapur		Junagadh		Samanko		Sadore	
	Base 1973–2002	Proj 2050	Base 1975–2004	Proj 2050	Base 1997–2010	Proj 2050	Base 1983–2009	Proj 2050
	Maximum temperature (°C)							
Jun	35.4	1.9	35.3	1.8	32.8	3.4	37.5	3.4
Jul	33.5	2.1	31.8	0.9	29.7	3.5	34.3	2.7
Aug	32.7	1.8	30.7	0.2	28.7	2.8	32.6	2.1
Sept	32.6	2.1	32.8	1.0	30.3	3.3	34.4	2.7
Oct	32.0	2.6	35.7	0.9	33.0	4.0	37.7	3.4
	Minimum temperature (°C)							
Jun	24.4	2.6	27.1	2.5	23.7	2.7	25.5	2.6
Jul	23.7	2.4	25.8	2.0	22.3	2.6	23.7	2.3
Aug	23.3	2.0	25.0	1.8	21.8	2.1	23.0	1.8
Sept	23.0	2.4	24.0	2.9	21.6	2.5	23.3	2.3
Oct	22.0	3.2	21.6	2.7	22.5	3.2	22.5	3.0
	Rainfall (mm) and % change							
Jun	55	−13	99	−50	170	−13	80	1
Jul	74	−16	327	19	228	−6	134	13
Aug	87	−3	148	55	315	−2	182	28
Sept	140	−1	67	54	223	−1	100	17
Oct	99	−13	43	45	79	−6	16	0

Base baseline climate, *Proj* projected change by 2050

adjacent layers (Ritchie 1998). Estimation of soil evaporation is based on the Sulieman-Ritchie model (Suleiman and Ritchie 2003). Actual plant water uptake (transpiration) is a function of potential water demand (potential transpiration) and supply (potential root water uptake) and is the minimum of either demand or supply. Root water uptake in each soil layer is computed by calculating a maximum water flow to roots using an approximation to the radial flow equation (Ritchie 1998). These calculations also account for root length density and soil water content in each layer. Root water uptake of each layer is then summed up to calculate potential root water uptake. This method for computing transpiration provides a functional approach for determining crop water stress. If the ratio of actual transpiration to potential transpiration is less than 1.0, photosynthesis is reduced in proportion to relative decreases in transpiration. If this ratio is less than 1.5, plant turgor and expansive growth of crops is reduced. The rationale for this is that as soil water becomes more limiting, turgor pressure in leaves would decrease and affect leaf expansion before photosynthesis is reduced.

In the model, high temperature influences growth and development and allocation of assimilates to the reproductive organs is reduced by decreased pod set and seed growth rate. The model's prediction of elevated temperature effects on pod yield were tested and shown to predict well (Boote et al. 2010) against elevated temperature data (Prasad et al. 2003). 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 model 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, personal communication). Increased CO_2 concentration reduces transpiration from the crop canopy via an empirical relationship between canopy conductance and CO_2 concentration. The model has been evaluated extensively against experimental data on cultivars, sowing densities, drought, and sowing dates collected in the USA (Gilbert et al. 2002), India (Singh et al. 1994a, b), Ghana (Naab et al. 2004), and Thailand (Anothai et al. 2009; Putto et al. 2009; Suriharn et al. 2011). The model has also been used to select best sites for testing breeding lines (Putto et al. 2009), to evaluate multi-environment trials (Anothai et al. 2009) and to determine optimum ideotypes (Suriharn et al. 2011). Thus the model has the potential to simulate groundnut growth and yield in response to agronomic management and genetic factors under both current and future climate conditions, such as high air temperatures, variability in rainfall and increased CO_2 concentrations in the atmosphere. The model assumes phosphorus availability to be non-limiting for crop growth; however, it simulates nitrogen fixation by the plant and responds to nitrogen availability in the soil. It simulates the effects of both water deficits and excess on plant growth and yield. The model also assumes that the 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 are described by Jones et al. (2003). Briefly, these include site characteristics (latitude and elevation), daily weather data (solar radiation, maximum and minimum air temperatures and precipitation), basic soil profile characteristics by layer (saturation limit, drained upper limit and lower limit of water availability, bulk density, organic carbon, pH, root distribution factor, runoff and drainage coefficients) and management data (cultivar, sowing date, plant population, row spacing, sowing depth and dates and amounts of irrigation and fertilizers applied). The cultivar data include the genetic coefficients or the cultivar-specific parameters (quantified traits) 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). Long-term records of weather data for the sites were obtained from the India Meteorological Department (IMD). The time period of the observed baseline weather data used for simulation was 1973–2002 for Anantapur and 1985–2007 for Junagadh. For the West Africa sites, the soils data for the dominant soil order were taken from the WISE database (Batjes 2012). Observed weather data were available only for Sadore. For other sites the weather data were downloaded from the National Aeronautics and Space Administration (NASA) website (http://power.larc.nasa.gov/). For the Samanko (Mali) site, the NASA rainfall data were replaced by the measured rainfall data of the site.

2.4 Model calibration of genetic coefficients

Calibration of Indian baseline cultivars JL 24 (Spanish type) and M 335 (Virginia type) was described in detail by Singh et al. (2012). The validation of genetic coefficients of these two cultivars was found to be satisfactory for further genetic evaluation of plant traits at the Indian sites. For calibrating the baseline cultivar 55–437 for West Africa, the data on crop phenology and yield were obtained from the breeders' trials conducted at three sites each in

Niger and Nigeria and one site in Mali. All the trials were rainfed. Fields were ploughed and prepared with tractor-driven implements and single super phosphate at 100 $kg ha^{-1}$ was applied at sowing each year. No nitrogen fertilizer was applied. Data on sowing dates was available only for Sadore. For the other sites only the information on sowing window (25 June to 10 July each year) was available. Plant spacing was 60 cm × 10 cm with the crop sown on ridges. For all trials, the data were available on dates to first and 50 % flowering and harvest date, above ground biomass (haulms) and pod yield, threshing percentage and seed size. About 40 % of crop data available from the three countries was used for calibrating the cultivar and the remaining was saved for model validation. To calibrate 55–437, the typical genetic coefficients of a Spanish type of groundnut cultivar were used and changes were made in the emergence to 50 % flowering (EM-FL) coefficient to match the simulated days to 50 % flowering with the observed data. 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. As the groundnut crop in the region is generally harvested prior to physiological maturity due to late leaf spot disease, the simulated days to maturity was purposely kept about 5 days longer than the reported data. 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 pod yield with the observed data of the sites. Simulated seed size and shelling percentage were 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). To match the simulated pod yields with the observed pod yields under water deficit conditions, the surface runoff and drainage coefficients given in the soil input file were also adjusted. Several iterations of model simulations were made to match the simulated yields with the observed yields at a site.

2.5 Development of virtual cultivars

To simulate crop response to the changes in genetic traits and climate scenarios, virtual cultivars incorporating various plant traits were developed from the three baseline cultivars (JL 24, M 335 and 55–437) calibrated for the Indian and West Africa conditions. These are described below.

2.5.1 Crop life cycle and yield potential traits

For developing virtual cultivars, three maturity durations of groundnut crop were considered—baseline (no change), 10 % shorter duration and 10 % longer duration. To make the crop duration 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 duration cultivar, these coefficients were increased by 10 % each. After making these changes, model simulations were carried out to check the accuracy in simulating the duration of different crop life cycle phases for the target sites. If not, minor adjustments were made in these coefficients to get the desired crop durations. 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. This gave six virtual cultivars consisting of three with, and three without, enhanced yield potential. 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:

$$WR(L) = EXP(-0.02^{*}Z(L)),$$

Where, *Z*(*L*) is the depth in meters to the midpoint of the 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:

$$WR(L) = [1.0 - Z(L)/5]^{p},$$

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 starting at 30-cm soil depth and below for greater soil water extraction. 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:

$$LL(TOL) = LL - 0.05^{*}(DUL - LL),$$

Where, *LL*(*TOL*) is the *LL* for the drought tolerant cultivar. The presumption is that a drought tolerant cultivar can extract water more effectively from each given layer.

2.5.3 Heat tolerance

Currently, heat (high temperature) tolerance is not a cultivar coefficient in the groundnut 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 groundnut species file to achieve a shift in tolerance to high temperature. The temperature tolerance of each of these three processes was increased by 2 °C in the species file of the groundnut model.

2.6 Projected climate change at the target 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 2050 time slice with 2.5 arc-minute resolution (5 km^2 resolution) and the WorldClim baseline (1960–90) climate data with 30 arc-second resolution (1 km^2 resolution) were downloaded for the target 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 (United Kingdom Met Office-Hadley Center Coupled Model, version 3) General Circulation Model for the A1B scenario as defined in the Special Report on Emission Scenarios (IPCC 2007). The difference between projected monthly maximum and minimum temperatures by 2050 and the baseline values gave changes in temperature. The percent deviations in monthly rainfall from the baseline values were also calculated (Table 2). Monthly changes in maximum and minimum temperature and rainfall along with CO_2 increase as per the ISAM model (IPCC 2001) were input to the 'environmental modifications section' of the management files of groundnut (.PNX). 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. As the rainfall was entered as a ratio, it affected the amount of each rainfall event rather than altering the pattern of rainfall distribution.

2.7 Simulating the impact of climate change and genetic traits

The groundnut model coupled with the seasonal analysis program available in DSSAT v4.5 was used to simulate the impact of climate change on groundnut productivity. Simulations were carried out for the baseline climate and the projected climate change by 2050 for each site. The impacts of changes in temperature (Temp.), changes in temperature and CO_2 (Temp. + CO_2) and changes in temperature, CO_2 and rainfall (Temp. + CO_2+Rain) were evaluated separately to quantify the impact of each factor. The atmospheric CO_2 concentration considered was 380 ppm for the baseline climate and 530 ppm for the 2050 climate projections (IPCC 2001).

For both the sites in India, the simulations were initiated on 15 May each year and the soil profile was considered to be at the lower limit (LL) of water availability on that day. Under normal sowing conditions the sowing window was 01 July to 15 August for Anantapur and 15 June to 30 July for Junagadh. The simulated crop was sown on the day when the soil moisture content in the top 30 cm soil depth had reached at least 40 % of the extractable water-holding capacity during the sowing window. Di-ammonium phosphate at 100 $kg\,ha^{-1}$ was applied at the time of sowing to supply 18 kgN and 20 kg P per ha to the crop. A plant population of 25 plants m^{-2} and row spacing of 30 cm were considered for simulating groundnut growth. Soil-limited photosynthesis factor (SLPF) of 0.74 was used for Anantapur and 0.87 for Junagadh. Site-specific values of SLPF were calibrated such that a single value of light-saturated leaf photosynthesis (AMAX) from literature accurately predicted biomass and yield over all sites. An SLPF value less than 0.90 represents soil limitations other than N or water. At all the sites the crop was grown rainfed in the model. Simulations were done for 30 years (1973–2002) for Anantapur and 22 years (1985–2007) for Junagadh.

For the West Africa sites, the sowing window was 25 June to 10 July and the soil water initialization and conditions to initiate sowing were the same as for the Indian sites. At the time of sowing, single super phosphate at 100 $kg\,ha^{-1}$ was applied and no nitrogen fertilizer was applied. Plant population assumed was 16.6 plants m^{-2} and row-to-row spacing of 60 cm. The SLPF value was 0.59 for Samanko and 0.55 for Sadore. Simulations were carried out for 14 years (1997–2010) for Samanko and 24 years (1983–2008) for the Sadore site. The crop was simulated as rainfed at all sites.

All the simulated data were analyzed using analysis of variance (ANOVA). Analyses were carried out to compare the performance of virtual cultivars within climate scenarios, or to compare the performance of a single virtual cultivar or tolerance trait across climate scenarios. To analyze data, the randomized complete block design (RCBD) was followed and the least significant differences at 5 % level of probability were calculated to compare the treatments. Years were considered as replications (blocks), as the groundnut yield under a treatment in a given year was not affected by another year (prior year carry-over of soil water was not simulated). The impact of climate change scenarios on yield of virtual cultivars was assessed relative to their respective mean values simulated for the baseline climate of the sites. The effect of changes in plant traits on yield of virtual cultivars was assessed by comparison to the mean pod yield of their counterparts (virtual cultivars without improved plant traits) simulated for the respective climate scenario of the sites. The impacts of drought and heat tolerance traits on the yield of groundnut were evaluated for the baseline and Temperature + CO_2 + Rainfall scenarios only.

3 Results

Singh et al. (2012) previously calibrated the baseline cultivars (JL 24 and M 335) for Indian sites and found a strong relationship between simulated and observed pod yields (cv. JL 24: Y=1.036X - 193.0, R^2=0.90; and cv. M 335: Y=0.929X+259.6, R^2=0.82). The *d*-value, a measure of model predictability (Willmott 1982), was also high for the cultivars (0.97 for JL 24 and 0.92 for M 335). Calibration of cultivar 55–437 for the West Africa sites also showed a strong relationship between simulated and observed pod yield (Y=1.11X-144.8, R^2=0.73 and *d*-value=0.91; Fig. 1). These results confirm that the genetic coefficients of the three baseline cultivars are accurate and the CROPGRO model can be reliably used to simulate growth and yield of groundnut in response to climate change factors and genetic modifications for different soil-climate environments of India and West Africa.

3.1 Response to genetic traits and climate scenarios in India

3.1.1 Anantapur

At Anantapur, the baseline cultivar JL 24 took 25 days to reach 50 % flowering, 106 days to physiological maturity and on average produced 1,228 kg of pod yield per ha under the baseline climate (Table 3). The short and long duration cultivars took 23 and 28 days to 50 % flowering and 95 and 117 days to physiological maturity, respectively. Under baseline climate and with a short growing cycle, pod yield decreased by 17 % and with long duration it increased by 15 %. By modifying the yield potential traits (LFMAX, XFRUIT and SFDUR), the pod yields of baseline, short, and long duration cultivars increased by 11 % each as compared to their counterparts with lower yield-potential traits. Pod yield of baseline cultivar significantly ($P<0.05$) decreased by 19 % (999 kg$\,$ha^{-1}) with the increase in

Fig. 1 Relationship of simulated pod yield of cultivar 55–437 with the observed yield across locations of West Africa

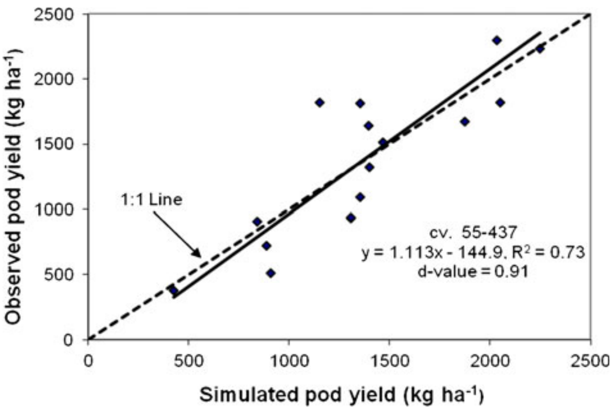

Table 3 Pod yield ($kg ha^{-1}$) of groundnut virtual cultivars derived from JL 24 under baseline climate and projected changes in temperature, CO_2 and rainfall by 2050 at Anantapur, India

	Baseline climate				Temp.		Temp. + CO_2		Temp. + CO_2 + Rain		
Cultivar	FL	PM	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	LSD (0.05)
Baseline	25	106	1228		999		1200		1171		64
10 % shorter	23	95	1018	−17	856	−14	1026	−15	1004	−14	63
10 % longer	28	117	1418	15	1131	13	1362	14	1319	13	70
Baseline + yield potential	25	106	1360	11[a]	1122	12[a]	1349	12[a]	1316	12[a]	72
10 % shorter + yield potential	23	95	1125	11[a]	950	11[a]	1142	11[a]	1117	11[a]	70
10 % longer + yield potential	28	117	1577	11[a]	1261	11[a]	1523	12[a]	1470	11[a]	72
LSD (0.05)	–	–	93	–	78	–	98	–	93	–	

FL days to 50 % flowering, *PM* days to physiological maturity, *% Ch* percent change in yield due to crop maturity or yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same column or row; [a] Yield improvement compared to the cultivar with same crop maturity

temperature. Under the temperature + CO_2 and the temperature + CO_2 + rainfall scenarios the yield reductions were 2 % (1,200 $kg ha^{-1}$) and 5 % (1,171 $kg ha^{-1}$), respectively. With the three climate change scenarios the pattern of change in yield of six virtual cultivars was the same as under the baseline climate. That is, the yield decreased by 14 to 15 % for the short duration cultivar, increased by 13 to 14 % for the long duration cultivar, and increased by 11–12 % by incorporating yield potential traits. These differences in yield of virtual cultivars due to crop maturity duration or yield potential were statistically significant ($P<0.05$). Across climate scenarios, maximum yields ranging from 1,261 $kg ha^{-1}$ to 1,577 $kg ha^{-1}$ were simulated for the longer duration cultivar with high yield potential, which represented 26 to 28 % increase in yield over the baseline cultivar yield simulated for the respective climate scenario. These results indicate that enhancing yield potential and increasing crop maturity by 10 % each made major contributions to yield increase under both baseline and future climate scenarios at the Anantapur site. When drought tolerance trait was incorporated in the virtual cultivars, the yields significantly ($P<0.05$) increased by 3 to 5 % under the baseline climate and 4 to 5 % under the climate change scenarios across virtual cultivars when compared to their counterparts without drought tolerance (Table 4). Incorporating heat tolerance did not increase the pod yield of virtual cultivars significantly under baseline climates, except for the longer maturity cultivar with yield potential traits. However, under climate change the pod yields increased by 5 to 9 %, which was statistically significant ($P<0.05$). These results indicate that yield gains were greater with improved drought tolerance than with heat tolerance under current climate; however under climate change, the heat tolerance will be relatively more important than drought tolerance for sustaining yields at Anantapur. The combined benefit of drought and heat tolerance ranged from 5 % to 7 % under baseline climates and 10 to 13 % under climate change scenarios across all virtual cultivars. Maximum yields of 1,694 $kg ha^{-1}$ under baseline climate and 1,660 $kg ha^{-1}$ under climate change were obtained when yield potential, drought and heat tolerance traits were incorporated in the longer maturity virtual cultivar.

Table 4 Effect of incorporating drought and heat tolerance traits on the mean pod yield (kg ha^{-1}) of virtual groundnut cultivars derived from JL 24 at Anantapur, India

		Drought tolerance		Heat tolerance		Drought + Heat tolerance		
Cultivar	Baseline pod yield	Pod yield	% change[a]	Pod yield	% change	Pod yield	% change	LSD (0.05)
	Baseline climate							
Baseline	1228	1271	3	1246	1	1292	5	28
10 % shorter	1018	1067	5	1033	2	1082	6	19
10 % longer	1418	1468	4	1461	3	1511	7	23
Baseline + yield potential	1360	1416	4	1382	2	1451	7	24
10 % shorter + yield potential	1125	1184	5	1144	2	1201	7	21
10 % longer + yield potential	1577	1651	5	1625	3	1694	7	28
	Climate change (Temperature + CO_2 + Rain)							
Baseline	1171	1225	5	1270	8	1328	13	34
10 % shorter	1004	1054	5	1068	6	1118	11	34
10 % longer	1319	1373	4	1434	9	1493	13	35
Baseline + yield potential	1316	1376	5	1414	7	1477	12	35
10 % shorter + yield potential	1117	1171	5	1168	5	1231	10	41
10 % longer + yield potential	1470	1534	4	1588	8	1660	13	36

[a] *% change* percent yield gain due to the trait compared to the baseline pod yield of a virtual cultivar with the same crop maturity and yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same row

3.1.2 Junagadh

At the Junagadh site, the baseline cultivar M 335 took 28 days to 50 % flowering, 124 days to physiological maturity and on average produced 2,229 kg of pod yield per ha under baseline climates (Table 5). The shorter and longer duration cultivars took 26 and 30 days to 50 % flowering and 113 and 134 days to physiological maturity, respectively. With the increase in temperature, the pod yield of baseline cultivar significantly ($P<0.05$) decreased by 17 % (1,859 kg ha^{-1}). Increase in temperature and CO_2 (Temp. + CO_2) brought pod yields back to the same level as simulated under the baseline climate. Increase in rainfall at the site (Temp. + CO_2 + rainfall) significantly ($P<0.05$) increased pod yield by 11 % (2,477 kg ha^{-1}) above the yield simulated under the baseline climate. Thus, the net effect of climate change on crop yield was positive at this site. Changing the duration of this cultivar had negligible effect on pod yield under the baseline and climate change scenarios. Increasing yield potential of virtual cultivars significantly ($P<0.05$) increased pod yield by 9 to 11 % across climate scenarios. Yield benefit due to drought tolerance was up to 7 % under the baseline climate and 5 to 7 % for the temperature + CO_2 + rainfall scenario (Table 6). Yield benefit due to heat tolerance across virtual cultivars was not significant under the baseline climate, but increased by 3 to 6 % with climate change, which was statistically significant. These results indicate that for the Junagadh site incorporating drought tolerance in groundnut is relatively more important than incorporating heat tolerance under both current and future climate. When both the drought and heat tolerance were considered together in virtual cultivars, the yield gain was up to 8 % under the baseline climate and up to 12 % under climate change. Maximum yield was simulated when yield potential, drought and heat tolerance traits were combined with

Table 5 Pod yield (kgha^{-1}) of groundnut virtual cultivars derived from M 335 under baseline climate and projected changes in temperature, CO_2 and rainfall by 2050 at Junagadh, India

	Baseline climate				Temp.		Temp. + CO_2		Temp. + CO_2 + Rain		
Cultivar	FL	PM	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	LSD (0.05)
Baseline	28	124	2229		1859		2245		2477		144
10 % shorter	26	113	2199	−1	1862	0	2260	1	2482	0	142
10 % longer	30	134	2226	0	1818	−2	2200	−2	2418	−2	140
Baseline + yield potential	28	123	2437	9[a]	2054	10[a]	2487	11[a]	2743	11[a]	155
10 % shorter + yield potential	26	113	2408	9[a]	2062	11[a]	2505	11[a]	2765	11[a]	155
10 % longer + yield potential	30	133	2430	9[a]	2005	10[a]	2427	10[a]	2674	11[a]	152
LSD (0.05)	–	–	100	–	85	–	104	–	107	–	

FL days to 50 % flowering, *PM* days to physiological maturity, *% Ch* percent change in yield due to crop maturity or yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same column or row; [a] Yield improvement compared to the cultivar with same crop maturity

longer duration cultivars under baseline climate (2,634 kgha^{-1}) and with short duration cultivar under climate change (3,017 kgha^{-1}) (Table 6).

Table 6 Effect of incorporating drought and heat tolerance traits on the mean pod yield (kgha^{-1}) of virtual groundnut cultivars derived from M 335 at Junagadh, India

		Drought tolerance		Heat tolerance		Drought + Heat tolerance		
Cultivar	Baseline pod yield	Pod yield	% change[a]	Pod yield	% change	Pod yield	% change	LSD (0.05)
	Baseline climate							
Baseline	2229	2377	7	2266	2	2398	8	56
10 % shorter	2199	2331	6	2234	2	2357	7	50
10 % longer	2226	2387	7	2270	2	2409	8	57
Baseline + yield potential	2437	2599	7	2469	1	2617	7	57
10 % shorter + yield potential	2408	2566	7	2432	1	2586	7	53
10 % longer + yield potential	2430	2602	7	2471	2	2634	8	53
	Climate change (Temperature + CO_2 + Rain)							
Baseline	2477	2615	6	2584	4	2734	10	73
10 % shorter	2482	2601	5	2616	5	2726	10	67
10 % longer	2418	2564	6	2555	6	2719	12	63
Baseline + yield potential	2743	2909	6	2833	3	3006	10	63
10 % shorter + yield potential	2765	2920	6	2851	3	3017	9	60
10 % longer + yield potential	2674	2856	7	2792	4	2988	12	59

[a] *% change* percent yield gain due to the trait compared to the baseline pod yield of a virtual cultivar with the same crop maturity and yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same row

3.2 Response to genetic traits and climate scenarios in West Africa

3.2.1 Samanko

The baseline cultivar 55–437 took 26 days to 50 % flowering, and 95 days to physiological maturity at Samanko under the baseline climate (Table 7). The shorter and longer duration cultivars took 24 and 28 days to 50 % flowering and 85 and 105 days to physiological maturity, respectively. On average, the pod yield under the baseline climate was 1,286 kg ha^{-1}, which increased by 3 % (1,325 $kgha^{-1}$) with the increase in temperature, and by 39 % (1,794 $kgha^{-1}$) with the increase in temperature and CO_2. In spite of projected decrease in rainfall at this site, the simulated mean pod yield was 1,799 $kgha^{-1}$ for the temperature + CO_2 + rainfall scenario. This indicates that because of current high rainfall and lower mean temperatures, the Samanko site will remain favourable for groundnut production under both current and future climates. Reducing crop duration by 10 % significantly ($P<0.05$) decreased the pod yields by 21 to 24 % across climate scenarios. However, increasing crop duration by 10 % increased the yield by 23 % under the baseline climate and up to 19 % under climate change scenarios, indicating the scope to enhance productivity of groundnut by growing longer duration varieties at Samanko. By modifying the yield potential traits of cultivars, the pod yield increased by 11 to 13 % as compared to their counterparts with low yield potential in different change climate scenario. Maximum yields ranging from 1,751 $kgha^{-1}$ to 2,364 $kgha^{-1}$ were simulated across climate scenarios when yield potential traits were combined with the 10 % longer maturity cultivar. This represented a 31 to 36 % increase in yield over the baseline cultivar yield in the respective climate scenario. Such a large response to this combination of traits is primarily attributed to the more favourable rainfall and temperature regimes at the Samanko site. Increase in pod yield with improved drought tolerance was negligible for the six virtual cultivars across climate scenarios (Table 8). Similarly, there was practically no effect of enhancing heat tolerance on pod yield of groundnut at Samanko across

Table 7 Pod yield ($kgha^{-1}$) of groundnut virtual cultivars derived from cultivar 55–437 baseline climate and projected changes in temperature, CO_2 and rainfall by 2050 at Samanko, Mali

	Baseline climate				Temp.		Temp. + CO_2		Temp. + CO_2 + Rain		
Cultivar	FL	PM	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	LSD (0.05)
Baseline	26	95	1286		1325		1794		1799		35
10 % shorter	24	85	977	−24	1036	−22	1405	−22	1417	−21	32
10 % longer	28	105	1582	23	1573	19	2119	18	2133	19	57
Baseline + yield potential	26	95	1428	11[a]	1469	11[a]	1984	11[a]	1991	11[a]	36
10 % shorter + yield potential	24	85	1106	13[a]	1159	12[a]	1567	12[a]	1584	12[a]	32
10 % longer + yield potential	28	105	1751	11[a]	1743	11[a]	2344	11[a]	2364	11[a]	57
LSD (0.05)	–	–	27	–	37	–	51	–	46	–	

FL days to 50 % flowering, *PM* days to physiological maturity, *% Ch* percent change in yield due to crop maturity or yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same column or row; [a] Yield improvement compared to the cultivar with same crop maturity

Table 8 Effect of incorporating drought and heat tolerance traits on the mean pod yield (kgha^{-1}) of virtual groundnut cultivars derived from cultivar 55–437 at Samanko, Mali

		Drought tolerance		Heat tolerance		Drought + Heat tolerance		
Cultivar	Baseline pod yield	Pod yield	% Change[a]	Pod yield	% Change	Pod yield	% Change	LSD (0.05)
	Baseline climate							
Baseline	1286	1286	0	1282	0	1286	0	6
10 % shorter	977	998	2	995	2	997	2	3
10 % longer	1582	1595	1	1572	−1	1588	0	13
Baseline + yield potential	1428	1435	0	1429	0	1435	0	6
10 % shorter + yield potential	1106	1109	0	1104	0	1107	0	2
10 % longer + yield potential	1751	1768	1	1752	0	1769	1	12
	Climate change (Temperature + CO_2 + Rain)							
Baseline	1799	1810	1	1807	0	1814	1	23
10 % shorter	1417	1421	0	1437	1	1442	2	14
10 % longer	2133	2153	1	2113	−1	2128	0	35
Baseline + yield potential	1991	2001	1	2002	1	2012	1	17
10 % shorter + yield potential	1584	1586	0	1589	0	1590	0	8
10 % longer + yield potential	2364	2380	1	2367	0	2384	1	24

[a] *% change* percent yield gain due to the trait compared to the baseline pod yield of a virtual cultivar with the same crop maturity and yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same row

virtual cultivars and climate scenarios. Incorporating both drought and heat tolerance had no significant effect on the yield of virtual cultivars, except for the 10 % shorter duration cultivar where 2 % increase in yield over the baseline yield was simulated. Maximum yield of 1,769 kgha^{-1} under baseline climate and 2,384 kgha^{-1} under climate change were simulated when drought and heat tolerance traits were incorporated in a longer maturity variety with high yield potential. This represented a 32 to 38 % increase in yield over the baseline yields simulated for the respective climate scenario (Table 8).

3.2.2 Sadore

The baseline cultivar 55–437 took 27 days to 50 % flowering and 94 days to physiological maturity at Sadore under the baseline climate (Table 9). The short and longer duration cultivars took 24 and 29 days to 50 % flowering and 85 and 104 days to physiological maturity, respectively. On average the pod yield with baseline climate was 759 kgha^{-1}, which significantly ($P<0.05$) decreased by 24 % (578 kgha^{-1}) with the increase in temperature and was restored to the baseline climate yield level with the increase in temperature plus CO_2. As the rainfall at this site is projected to increase, the mean pod yield further increased to 792 kgha^{-1} under the temperature + CO_2 + rainfall scenario. Reducing crop maturity by 10 % significantly ($P<0.05$) decreased the pod yield by 12 % under the baseline climate, and up to 9 % with climate change scenarios. However, increasing crop maturity by 10 % significantly ($P<0.05$) increased pod yield by 7 % under the baseline climate and had negligible effect on pod yield with climate change scenarios, indicating that longer duration

Table 9 Pod yield (kgha^{-1}) of groundnut virtual cultivars derived from cultivar 55–437 baseline climate and projected changes in temperature, CO_2 and rainfall by 2050 at Sadore, Niger

Cultivar	Baseline climate				Temp.		Temp. + CO_2		Temp. + CO_2 + Rain		LSD (0.05)
	FL	PM	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	Pod yield	% Ch	
Baseline	27	94	759		578		758		792		37
10 % shorter	24	85	671	−12	532	−8	697	−8	722	−9	30
10 % longer	29	104	815	7	581	1	761	0	798	1	35
Baseline + yield potential	27	94	842	11[a]	654	13[a]	855	13[a]	896	13[a]	42
10 % shorter + yield potential	24	85	746	11[a]	604	14[a]	790	13[a]	822	14[a]	34
10 % longer + yield potential	29	104	904	11[a]	656	13[a]	860	13[a]	904	13[a]	40
LSD (0.05)	–	–	39	–	31	–	42	–	43	–	

FL days to 50 % flowering, *PM* days to physiological maturity, *% Ch* percent change in yield due to crop maturity or yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same column or row; [a] Yield improvement compared to the cultivar with same crop maturity

cultivars may not be beneficial in future climate scenarios at Sadore. Enhancing yield potential increased pod yield by 11 to 14 % across climate scenarios as compared to the yield of their counterparts with low yield potential. Maximum yield ranging from 656 kgha^{-1} to 904 kgha^{-1} was simulated when the high yield potential traits were combined with the longer duration cultivar, which represented 14 to 19 % increase in yield over the baseline cultivar yield simulated for the respective climate scenario. These results indicate that enhancing the yield potential will be more useful for increasing yields at Sadore with some adjustments in crop duration to match the water availability period in future (Table 9). Incorporating drought tolerance significantly ($P<0.05$) increased pod yield of virtual cultivars up to 15 % under the baseline climate and up to 17 % under climate change (Table 10). Under baseline climate, the benefit of incorporating heat tolerance was significant ($P<0.05$) only for the shorter and longer maturity cultivars, which was limited to a 3 % increase in yield. This benefit significantly increased by 9 to 12 % with climate change, indicating the importance of heat tolerance in groundnut in future at Sadore. Incorporating both drought and heat tolerance significantly ($P<0.05$) increased pod yield by 14 to 18 % under the baseline climate and 25 to 31 % under climate change, again indicating the need of incorporating these two traits in groundnut for increasing and sustaining yield at Sadore. Maximum yields of 1,069 kgha^{-1} under baseline climate and 1,165 kgha^{-1} under climate change were simulated when both drought and heat tolerance were combined with longer duration cultivars with high yield potential. These yields represented 41 to 47 % increase in yield as compared to the baseline cultivar yield in the respective climate scenario.

4 Discussion

Using the groundnut model, we have quantified the contribution of crop maturity, yield potential, drought and heat tolerance traits and their combinations on groundnut yield under the current and future climates of the target sites in India and West Africa. As climate change

Table 10 Effect of incorporating drought and heat tolerance traits on the mean pod yield ($kg ha^{-1}$) of virtual groundnut cultivars derived from cultivar 55–437 at Sadore, Niger

		Drought tolerance		Heat tolerance		Drought + Heat tolerance		
Cultivar	Baseline pod yield	Pod yield	% change[a]	Pod yield	% change	Pod yield	% change	LSD (0.05)
	Baseline climate							
Baseline	759	870	15	775	2	885	17	18
10 % shorter	671	758	13	689	3	771	15	15
10 % longer	815	938	15	840	3	964	18	20
Baseline + yield potential	842	963	14	858	2	980	16	18
10 % shorter + yield potential	746	839	13	761	2	849	14	15
10 % longer + yield potential	904	1040	15	932	3	1069	18	21
	Climate change (Temperature + CO_2 + Rain)							
Baseline	792	924	17	879	11	1024	29	25
10 % shorter	722	837	16	806	12	929	29	21
10 % longer	798	931	17	895	12	1046	31	26
Baseline + yield potential	896	1045	17	978	9	1137	27	27
10 % shorter + yield potential	822	951	16	896	9	1026	25	22
10 % longer + yield potential	904	1056	17	1000	11	1165	29	28

[a] *% change* percent yield gain due to the trait compared to the baseline pod yield of a virtual cultivar with the same crop maturity and yield potential traits, *LSD (0.05)* least significant difference at 5 % level of probability to compare pod yields within the same row

will alter the length of growing period (LGP) due to changes in rainfall and temperature, the first step to achieve higher yields is to fit the maturity duration of the crop to the changing LGPs. This will minimize possible water and heat stress to the crop during its life cycle. The study revealed that with 10 % longer maturity cultivars, 13 to 19 % increase in pod yield could be realized at Anantapur and Samanko sites under climate change; whereas at Sadore, longer maturity cultivar was not beneficial. At the Junagarh site, in spite of increase in rainfall, the current maturity duration of the baseline cultivar will hold well under the future climate. Fitting crop maturity to the changed LGPs in future will be an easy adaptation process because sufficient genetic variability exists in maturity traits among groundnut genotypes. Enhancing yield potential by increasing maximum leaf photosynthesis rate (LFMAX), fraction of daily growth partitioned to pod (XFRT) and seed-filling duration (SFDUR) each by 10 %, increased yields at all the four target sites. The yield increases ranged from 9 % to 14 % across sites in different climate scenarios. As high yield potential of the crop was achieved by increasing the capacity of both source (changing LFMAX) and sink (changing XFRT and SFDUR), the yield gains were much higher than the yield gains of 3 to 4 % simulated for soybean by increasing LFMAX only (Boote et al. 2003). Such high yield gains in case of groundnut crop are possible, as this crop has sufficient genetic variation in photosynthesis rate, partitioning intensity, and harvest index, and photosynthesis has been reported to have positive association with total sink size, pod yield and harvest index (Nautiyal et al. 2012). The non-senescence character of groundnut could also be one reason for such high yield gains with increased LFMAX.

The benefits of incorporating drought tolerance in groundnut were variable depending upon the amount and distribution of rainfall and water retention properties of the soil profiles at the target sites. Under the baseline climate, the simulated yield gains due to drought tolerance were the largest (up to 15 %) at the Sadore site, followed by Junagadh (up to 7 %), Anantapur (up to 5 %) and Samanko (up to 2 %). Except for the Samanko site because of high rainfall, the percent yield gains of virtual cultivars due to drought tolerance will either remain the same or increase with climate change at the sites. Though drought tolerance in groundnut may be attributed to many plant traits, increased root length density in the subsoil resulting in greater water extraction during the period of water deficit is the likely mechanism of drought tolerance for higher yields (Songsri et al. 2008; Painawadee et al. 2009; Jongrungklang et al. 2011). Thus the approach used in the model to simulate the benefits of drought tolerance is appropriate. While drought is the major yield-reducing factor under current climates, temperature increase with climate change will reduce yields drastically at the warmer sites such as Sadore. Thus incorporating heat tolerance in groundnut will increase yields by 9 to 12 % under future climates at Sadore, followed by Anantapur (5–9 %) and Junagadh (3 to 6 %). As the Samanko site currently has high rainfall and moderate temperatures during the growing season, incorporating heat tolerance will not benefit the crop in near future. Heat tolerance among groundnut genotypes has been reported by Ntare et al. (2001) for the Sahelian environment and by Craufurd et al. (2003) in controlled environment studies, thus it will be possible to breed cultivars for higher yield for the future climate conditions of the sites. The yield gains due to heat tolerance simulated in this study are also realistic as the mechanisms for yield losses due to high temperature stress in the groundnut model are the same as reported by Prasad et al. (2003) and Craufurd et al. (2003) and the model has been validated by Boote et al. (2010) for the high temperature effects on groundnut crop. These results showed that the response of virtual cultivars to drought tolerance traits is influenced by the soil water retention characteristics and the current and future rainfall regimes of the sites. The cultivar response to heat tolerance traits under climate change is primarily determined by the current temperature regimes of the sites, and is further modified to some extent by the rainfall regime of the sites. The results obtained at the target sites in India and West Africa can be extended to other sites with similar climatic and edaphic conditions. The simulation approach used to develop and evaluate virtual cultivars for drought and heat tolerance, along with the model itself, can be useful for developing crop adaptation strategies under climate change in other groundnut regions of the world.

5 Conclusions

It is concluded that different combination of plant traits will be needed to increase and sustain productivity of groundnut under current and future climates of the four target sites in India and West Africa. Enhancing yield potential traits consistently increased crop yields under both current and future climates of the sites. Increasing crop maturities increased yields at Anantapur and Samanko, but not at Junagadh and Sadore sites. In current climates at Anantapur, Junagadh and Sadore, yield gains were larger with improved drought tolerance than heat tolerance, however, yield gains due to both traits increased under climate change at these sites. At Samanko, yield gains due to improved drought tolerance were marginal with no benefits accrued from heat tolerance under current and future climates. The results obtained at the target sites are transferable to other sites with similar climatic and edaphic conditions. The CROPGRO-Groundnut model and the simulation approach used to develop and evaluate virtual cultivars for drought and heat tolerance can be useful for developing crop adaptation strategies under climate change in the groundnut regions of the world.

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