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An integrated crop model and GIS decision support system for assisting agronomic decision making under climate change

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HIGHLIGHTS

- The study assessed the impact of climate change on groundnut yields in dry areas
- Adaptation strategies are the key for improving yields under climate change
- Crop models can be used as a scientific tools for evaluation of adaptation options
- Linking crop models with GIS provided opportunity for spatial analysis of yields

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ABSTRACT

The semi-arid tropical (SAT) regions of India are suffering from low productivity which may be further aggravated by anticipated climate change. The present study analyzes the spatial variability of climate change impacts on groundnut yields in the Anantapur district of India and examines the relative contribution of adaptation strategies. For this purpose, a web based decision support tool that integrates crop simulation model and Geographical Information System (GIS) was developed to assist agronomic decision making and this tool can be scalable to any location and crop. The climate change projections of five global climate models (GCMs) relative to the 1980–2010 baseline for Anantapur district indicates an increase in rainfall activity to the tune of 10.6 to 25% during Mid-century period (2040–69) with RCP 8.5. The GCMs also predict warming exceeding 1.4 to 2.4 °C by 2069 in the study region. The spatial crop responses to the projected climate indicate a decrease in groundnut yields with four GCMs (MPI-ESM-MR, MIROC5, CCSM4 and HadGEM2-ES) and a contrasting 6.3% increase with the GCM, GFDL-ESM2M. The simulation studies using CROPGRO-Peanut model reveals that groundnut yields can be increased on average by 1.0%, 5.0%, 14.4%, and 20.2%, by adopting adaptation options of heat tolerance, drought tolerant cultivars, supplemental irrigation and a combination of drought tolerance cultivar and supplemental irrigation respectively. The spatial patterns of relative benefits of adaptation options were geographically different and the greatest benefits can be achieved by adopting new cultivars having drought tolerance and with the application of one supplemental irrigation at 60 days after sowing.

1. Introduction

Climate change is one of the most important challenges being faced by humanity that has serious implications on global food security. Its impacts have already been significant on water resources, length of growing season, and food security, especially in the semi-arid tropical regions (IPCC, 2007). The climate model projections based on the Inter-Governmental Panel on Climate Change (IPCC) Fifth Coupled Model Intercomparison Project (CMIP5), reveal that surface air temperatures including night time temperatures are expected to further increase compared to the baseline conditions (IPCC, 2014). Under the business-as-usual scenario, mean warming over India is likely to be in the 1.7–2.0 °C range by the 2030s and in the 3.3–4.8 °C range by the 2080s relative to pre-industrial times. All-India rainfall under the business-as-usual scenario, is projected to increase from 4% to 5% by 2030s and from 6% to 14% towards the end of the century (2080s) compared to the 1961–1990 baseline (Chaturvedi et al., 2012). Over the past 20th century, in the temperate regions of northern hemisphere average rainfall increased with more frequent extreme heavy rainfall events and in contrast rainfall in subtropics decreased and droughts have become more intensive and frequent in Asia and Africa (IPCC, 2007).

Climate change in terms of changes in temperature, rainfall patterns, and increased carbon dioxide (CO_2) levels will impact agriculture,

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especially in the rainfed regions. Crop productivity is expected to alter due to these changes in climate, extreme weather events and changed scenario of pests and diseases. Increased carbon dioxide concentration in the atmosphere is beneficial for plant growth, and controlled experiments have demonstrated that elevated CO_2 concentrations can increase plant growth while enhancing water use efficiency (Walthall et al., 2012). The impacts of climate change on agriculture will differ across locations. Determining how climate change will affect agriculture is highly uncertain and complex as a variety of effects are likely to occur (Roudier et al., 2011; Knox et al., 2012; Muller et al., 2011). Production practices may require major adjustments. Adaptation measures such as developing drought, pest, and heat tolerant cultivars, diversifying crop rotations, integrating livestock into crop production systems, and nutrient efficient systems may be required to minimize impacts on productivity. Therefore, determining the location-specific impacts of climate change on crop production and water resources is essential in order to develop possible adaptation strategies (Howden et al., 2007; Lobell et al., 2008; Thornton et al., 2009; Godfray et al., 2010).

Groundnut (*Arachis hypogaea* L.) is an important oilseed crop grown by small and marginal farmers. In India the crop is mainly grown under rainfed conditions during the main rainy season (June–October). As climate change is becoming more intense and demand for edible oil and vegetable protein in India is increasing, the groundnut production needs to be improved to meet the future demand. This can be possible only by developing new agronomic technologies and cultivars which has greater tolerance to elevated temperatures and responsive to raising CO_2.

Crop simulation models are valuable tools for evaluating the potential effects of environmental, biological and management factors on crop growth and development. They have been evaluated and used for many soil and environmental conditions across the world and have in the past, been successfully used in yield predictions (Jagtap and Jones, 2002), irrigation planning for crops (Behera and Panda, 2009), optimization of irrigation water use (Fortes et al., 2005; Bulatewicz et al., 2009), and understanding the climate change impacts on various crops (Krishnan et al., 2007; You et al., 2009; Reidsma et al., 2010; Singh et al., 2014a). They have also been used for comparison of various scenarios and strategies such as quantifying the potential benefits of incorporating drought, heat tolerance and yield-enhancing traits into commonly grown cultivars under climate change in chickpea (Singh et al., 2012, 2014a,b; Rinaldi, 2004; Rinaldi et al., 2007), analysis of yield trends over time (Liu et al., 2011), and in many more applications. Crop simulation models need to be applied at larger scales to be economically useful to analyze the effects of various alternate management strategies across the watershed or the region (Naresh Kumar et al., 2013; Mishra et al., 2013). Global studies on linking crop models with a Geographical Information System (GIS) have demonstrated the strong feasibility of crop modeling applications at a spatial scale. Most agricultural operations closely connected with natural resources that vary spatially and GIS, which is capable of using spatial data, can be very handy in environmental and agricultural modeling. Several researchers have successfully used crop models and GIS to study spatial water requirement of crops, yield forecasting and climate change impacts at watershed and regional scales. The objectives of the present study were to quantify the spatial variability in groundnut yields under (a) current climate, (b) climate change and (c) to provide strategies of cultivar, water and fertilizer application aimed at enhancing production or reducing investment inputs in groundnut under climate change conditions.

2. Material and methods

2.1. Study area

The study area of Anantapur district is in the state of Andhra Pradesh in India. It lies between 13′–40′ and 15′–15′ Northern Latitude and 76′–50′ and 78′–30′ Eastern Longitude. It is skirted by Bellary and Kurnool district on the North, Kadapa district to the southeast, and Kolar district to the North (Fig. 1). Agriculture is the most important economic activity and source of livelihood in the district. Anantapur is the only arid district in the State with an annual mean rainfall of 598 mm (1980–2010) with a coefficient of variation (CV) of 28%. The higher CV of rainfall relative to the threshold level of 25% for annual rainfall suggests variability and a lower degree of dependability on rainfall. Alfisols are the predominant soils (78% of the area), followed by Vertic Inceptisols (20%), and other soils are (2%). The soils based on soil texture can be classified as sandy loams (31%), clay (24%) loamy sands (14%), sandy clay loams (13%) and rocky lands (12%). Groundnut (*A. hypogaea* L.) is an important oilseed and food crop grown by small and marginal farmers in the district. Its yields have often been unpredictable due to low and erratic distribution of rainfall coupled with many other biotic factors. Average pod yield was observed to be 516 kg/ha and varies between a little over 200 kg/ha and 1200 kg/ha from year to year. Evidence from earlier studies reveals that in years when seasonal rainfall was 10% less than normal, yields were reduced drastically by 42% (Bapuji Rao et al., 2011). In addition to these problems climate change poses a new threat to the groundnut cultivation in Anantapur.

Anantapur district can be divided into four natural divisions based on soil types, elevation and rainfall, Northern region with 14 mandals (administrative unit), Central region with 24 mandals, Highland region with 12 mandals and Southern region with 13 mandals.

2.2. System inputs

2.2.1. Climate data

Thirty-years (1980–2010) of observed daily weather data were obtained from the ANGR Agricultural University Agromet observatory located at Anantapur. The baseline weather datasets were quality controlled and inspected for outliers or anomalous values and if found, such values were adjusted and corrected using bias corrected AgMERRA data. AgMERRA consists of historical climate datasets, which were prepared based on a combination of daily outputs from retrospective analyses ("reanalyses"), gridded temperature and precipitation station observations, and satellite information for solar radiation and rainfall (Ruane et al., 2015). In order to create a representative 30-year weather series for each location, neighboring sites from the highly spatially resolved WorldClim data, which is available historically as monthly values, were used. A total of 72 farm climate sites were used for Anantapur district (Fig. 2).

Projections of future climate were obtained using CMIP5 and the Representative Concentration Pathways (RCP) for carbon emissions currently in use by the IPCC Fifth Assessment Report (IPCC, 2014). Future climate projections were created using the "delta" method, in which the mean monthly changes (from baseline) for RCP 8.5 for Near, Mid and End Century time slices centered around 2030, 2055 and 2080, respectively, were applied to the daily baseline weather series. These monthly changes were imposed on baseline climate series for all selected sites by adding temperature changes to the baseline record and multiplying by a precipitation change factor. The future time scale weather series and the corresponding projected CO_2 concentration, according to RCP 8.5, were used in all crop model simulations. We refer to these future projections as "mean change scenarios". This procedure was repeated for each of the five global climate models (GCMs). The five GCMs used in this study are as follows:

a) CCSM4: Community Climate System Model developed by the University Corporation for Atmospheric Research, Boulder, CO, USA
b) GFDL-ESM2M: Geophysical Fluid Science Laboratory-Earth System Modeling developed by Princeton University, Princeton, NJ, USA
c) HadGEM2-ES: Hadley Centre Global Environment Model version 2. developed by Met Office Hadley Centre, UK
d) MIROC5: Model for Interdisciplinary Research on Climate, Japan

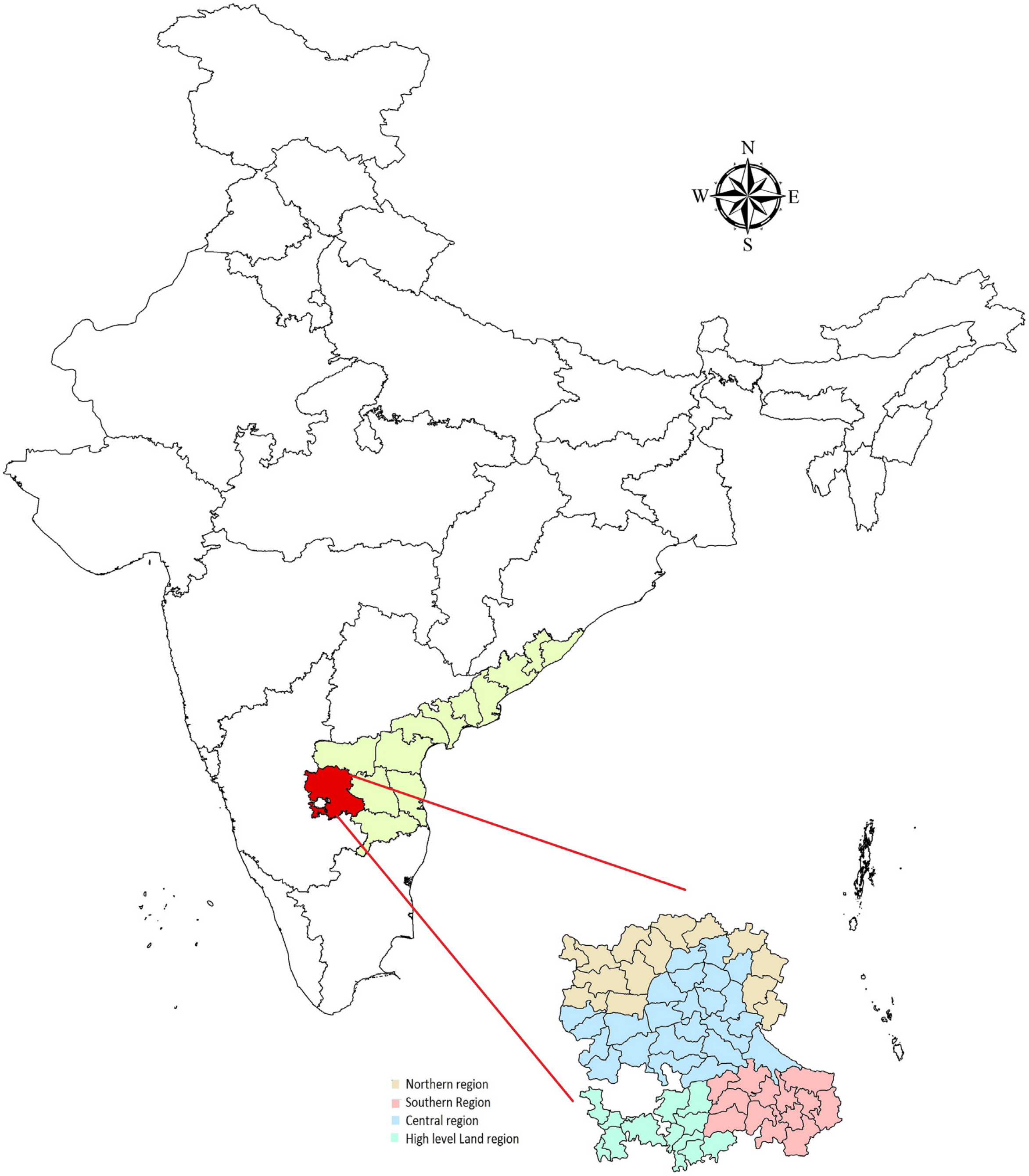


Fig. 1. Location of the study area in Anantapur district, Andhra Pradesh, India.

e) MPI-ESM-MR: Max-Planck-Institute Earth System Model running on medium resolution grid, Hamburg, Germany.

2.2.2. Soil data

Five different soil profiles of the soil orders were used (Fig. 2). The farm locations were then mapped on the Anantapur soil map developed by the National Bureau of Soil Survey and Land Use Planning (NBSS&LUP), Nagpur and the representative soil profile for each farm location point was prepared. Physical and chemical properties of the soil such as texture, hydraulic parameters, bulk density, organic matter and available N were estimated for each location based on the available soil profile data and expert knowledge. Additional soil parameters such as, soil albedo, drainage constant, and runoff curve number were estimated based on the soil texture data from the generic soil database available in the Decision Support System for Agrotechnology Transfer (DSSAT)-models (Tsuji et al., 1998).

2.3. The CROPGRO-Peanut model

The CROPGRO-Peanut model available in DSSAT v 4.5 simulates crop growth and development on daily time step. Soil water balance in the model is estimated based on Ritchie's water balance model (Ritchie, 1998). This is a one-dimensional model that computes daily changes in soil water content in a soil layer due to infiltration, irrigation, vertical drainage, unsaturated flow, soil evaporation, plant transpiration and root water uptake. Infiltration is calculated on the difference between rainfall (or irrigation) and runoff. Drainage is assumed to be constant

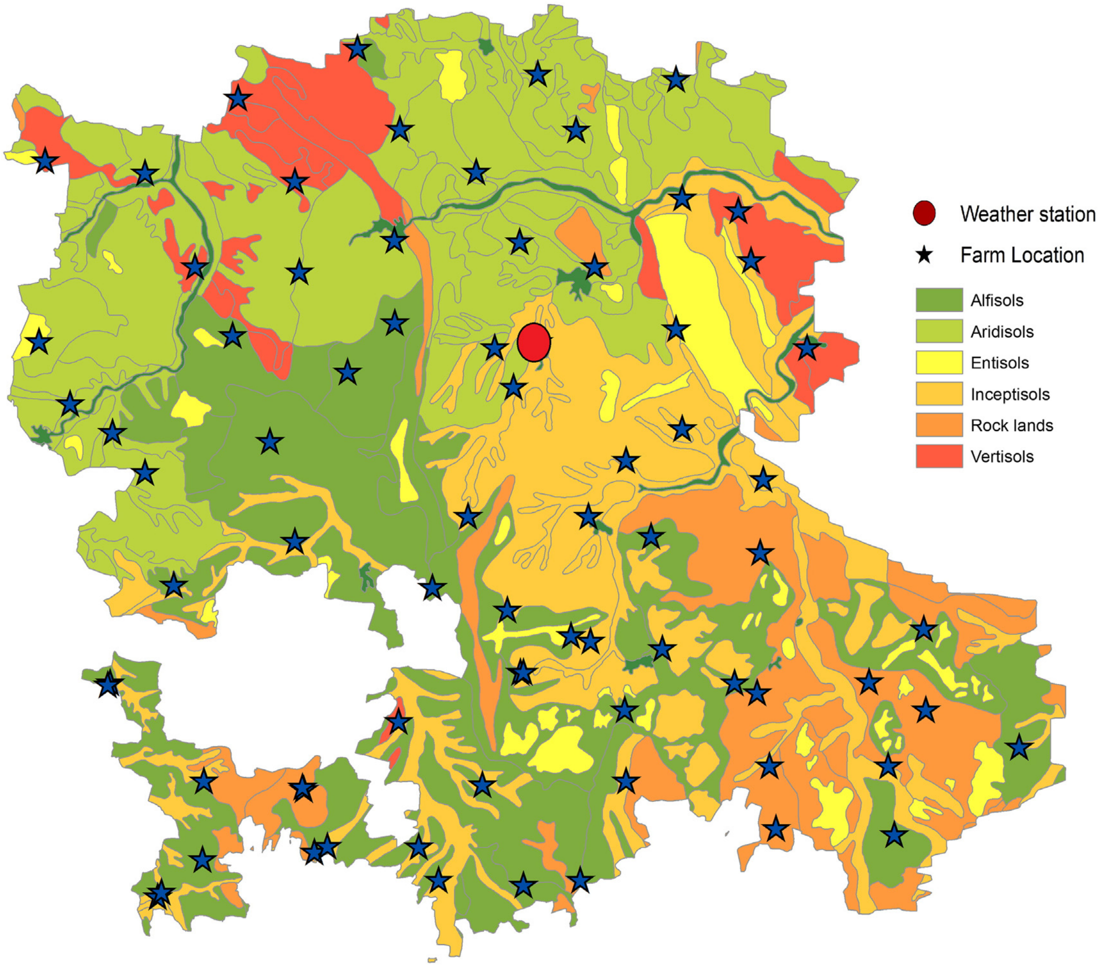


Fig. 2. Map showing the soils (source: NBSS&LUP, Nagpur), weather station and farm climate locations.

throughout the whole day and computed for each layer using the drained upper limit and lower limit values of soil water content. When the water content in each layer is above the drained upper limit, water drains to the next layer. The amount of water passing to each layer is then compared to statured hydraulic conductivity (Ksat) of that layer. If the Ksat is less than the drainage then the actual drainage is limited to the Ksat value. The model uses the Priestly–Taylor method to estimate daily potential evapotranspiration. It requires cultivar coefficients (cultivar-specific parameters) as an input to the model in addition to crop-specific coefficients that are considered less changeable or more conservative in nature across crop cultivars. The model can also simulate the impact of elevated temperatures on groundnut growth and development. High temperature influences growth and development and allocation of assimilates to the reproductive organs is reduced by decreased pod set and seed growth rate (Singh et al., 2014b). Similarly increased CO_2 concentration in the atmosphere increases crop growth through increased leaf-level photosynthesis, which responds to CO_2 concentration using simplified RUBISCO kinetics similar to Farquhar and von Caemmerer (1982).

2.3.1. Model calibration and determination of genetic coefficients

Model calibration involves the estimation of genotype coefficients to confirm an agreement between model predictions and observed values. The present model was calibrated for groundnut cultivar JL-24 with the data sets available with the International Crops Research Institute for the Semi-Arid-Tropics (ICRISAT) for the 1986–1991 seasons and multi-site Initial Variety Trials-II (IVT-II) data obtained from the Annual Reports of the All India Coordinated Research Project on Groundnut (Singh et al., 2012).

2.3.2. Virtual cultivars

Virtual cultivars that were developed by modifying various plant traits of JL-24 (Singh et al., 2014b) in addition to regular crop management decisions were used as one of the adaptation strategies. The main idea of testing drought and heat tolerant virtual cultivars in the study region was, the projected climate changes in this region will intensify the problems of heat and drought stress during critical periods of crop growth and hence we thought that cultivars having drought and heat tolerance will improve the groundnut yields. Different virtual cultivars included the following:

a) JL-24 with longer life cycle—To lengthen crop duration, the calibrated and evaluated genetic coefficients of JL-24 which determines 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.
b) JL-24-with heat tolerance—In the groundnut species file the temperature tolerance was increased by 2 °C for pod set, individual pod plus seed growth rate and partitioning of assimilates to reproductive organs processes which are mainly influenced by high temperatures.
c) JL-24 with drought tolerance—Changes were made in the relative root distribution function (WR) and the lower limit of soil water availability (LL) for each soil layer presuming that a drought tolerant cultivar has greater rooting density with depth in the soil profile for

greater access and mining of soil water, to enable extraction of water more effectively from each given soil layer.

2.3.3. Management decisions

2.3.3.1. Supplemental irrigation. Supplemental irrigation is one of the management options studied which will be attractive to farmers and helps to address the financial risk associated with climate variability in groundnut. The current analysis simulated the impact of an irrigation application at 60 days after planting coinciding with the pod development stage.

2.4. Decision support system architecture

The decision support system linked with GIS receives spatial information on soil and weather from the built-in database, passes them to a process based crop simulation model for simulating crop growth and yield. The system enables spatial analysis of crop yield by running the crop simulation model for many locations. Location-wise inputs required for the crop model are generated from spatial layers of soil and weather data generated using highly spatially resolved WorldClim data. Fig. 3 shows the broad framework of the decision support system with linkages between the GIS tools and crop simulation model and the architecture of the system. The system consists of four major

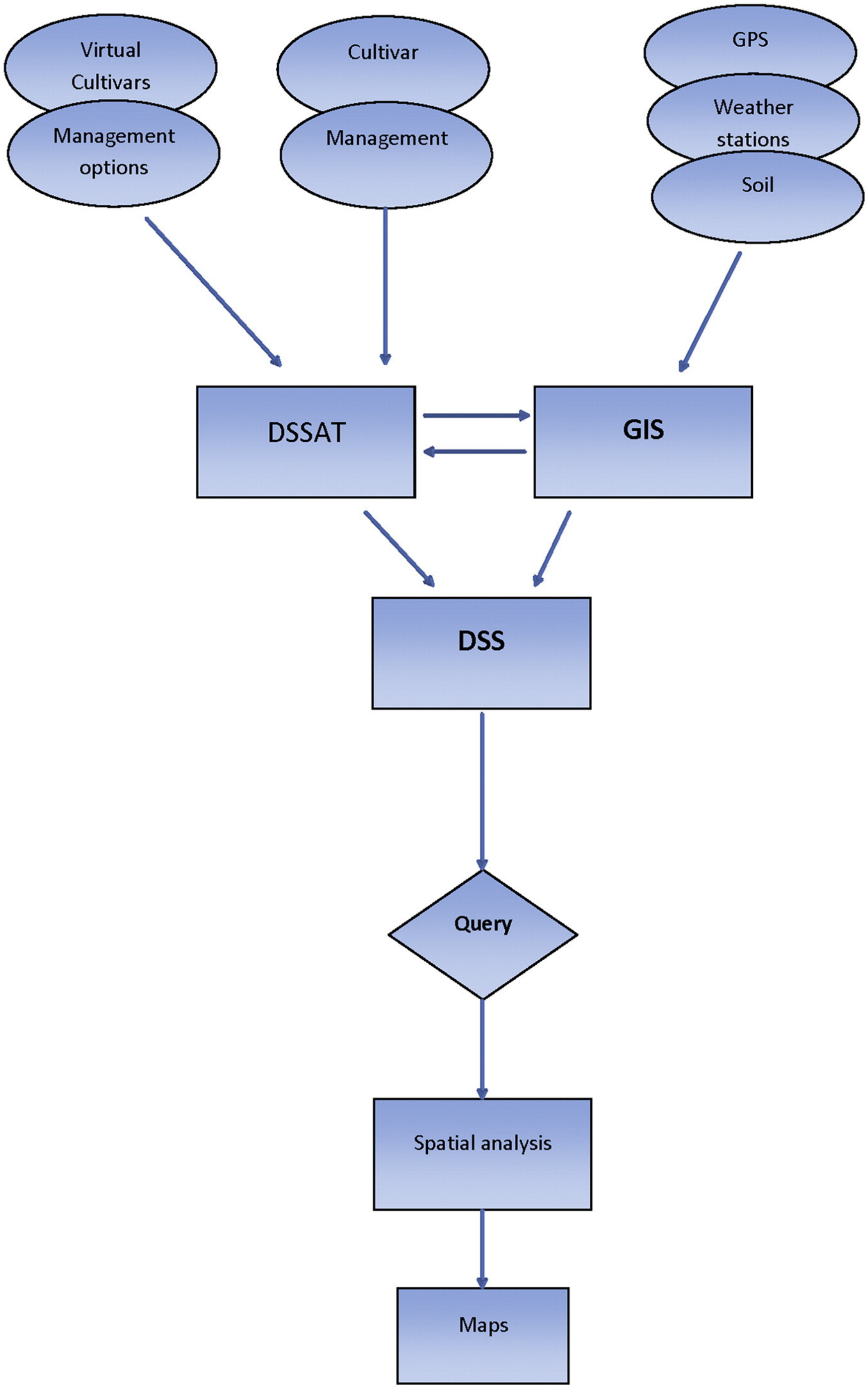


Fig. 3. Basic architecture of the decision support system.

components: (a) inputs assimilating GIS system, (b) DSSAT crop simulation model, (c) querying system and (d) spatial output generating system.

Seventy two representative locations were selected in the study area, for which soil and climate data and all other inputs required by the CROPGRO-Peanut model were provided from the database developed. Simulations were carried out for each location under current and future climate conditions using virtual cultivars and management options. The modeled outputs at each point location were assimilated into GIS. Using ordinary krigging interpolation, spatial yield maps were generated for the Anantapur district to visualize the impact of climate change and various adaptation strategies on groundnut yield. A simple visualization tool was developed using Dot Net framework and Microsoft Structured Query Language (MS SQL) server as a data base and hosted in a high-end server using the outputs generated from GIS. This tool enables the user to spatially compare groundnut yields under different climate change scenarios compared to the base period with and without adaptation options. The tool can be accessed online (http://spatial-tools.icrisat.ac.in/). A desktop standalone application was also developed to work offline.

2.4.1. Simulation of crop yields

DSSAT's seasonal analysis option which allows multiple years run with the same initial conditions was used to simulate the effects of climate variability on groundnut yields for each of the 72 locations to study the impact of virtual cultivars and management scenarios using historical baseline weather data (1980–2009). The aim was to (a) ascertain the most suitable management/cultivar options that resulted in the highest baseline yield and (b) understand how this combination might perform under climate change conditions. Simulations were carried out for the baseline climate and the projected climate change during Mid-century period for each site. The simulations were initiated a month before sowing date each year and the soil profile was considered to be at 50% available water on that day of sowing. Under normal sowing conditions the sowing window was 1 July to 15 August and under delayed conditions the sowing for Anantapur is from 15th July to 15th August. The simulated crop was sown on the day cumulative rainfall in that particular window reached 50 mm in seven days. Recommended nitrogen (20 kg/ha) was applied at the time of planting. A plant population of 25 plants m^2 with row spacing of 30 cm was considered for simulating groundnut growth. Soil-limited photosynthesis factor (SLPF) of 0.74 was used for Anantapur (Singh et al., 2014b).

3. Results of decision support system

Seventy two location specific simulations were carried out in Anantapur district. The soils in the study area are mostly dominated by Alfisols and Aridisols followed by Inceptisols, Entisol and Vertisols. The soil carbon values ranged from 0.49 to 0.96% and the extractable water holding capacity of soil ranged from 90 to 165 mm.

3.1. Future climate characteristics relative to baseline

Mean crop season rainfall changes are both highly significant and spatially heterogeneous across Anantapur district. Two critical points were evident from the spatial distribution of the rainfall data. Firstly, there is an overall increase in crop season rainfall. The average projections of 5 GCMs relative to baseline data (1980–2009) showed a 10.6–25% increase during Mid-Century period (2040–69) with RCP 8.5 with MPI-ESM-MR showing the least and GFDL-ESM2M shows the highest increase in rainfall (Fig. 4). The spatial distribution maps of rainfall also showed increased rainfall activity in northern and southern Anantapur district compared to the baseline. Secondly, increase in September and October rainfall in all the GCMs studied was noted, which will have positive impact on crop growth and development (Fig. 5). The spatial analysis of rainfall data reveals that increased rainfall activity will be observed in all the regions of Anantapur. The average increases in rainfall as predicted by five GCMs will be pronounced in the northern region (19%) followed by the central region (17.4%) southern region (16.8%) and high level land (16.7%).

Changes in mean crop season temperatures were predicted by five GCMs. Warming exceeding 1.4–2.4 °C by 2069 was predicted in Anantapur district, with MIROC5 predicting more warming and HadGEM2-ES lesser warming. More warming will be observed in the eastern parts of the district. Spatial analysis of temperature changes indicated almost uniform changes across all the regions. Minimum temperatures was more (2.33–2.46 °C) than the maximum temperatures (1.84–1.88 °C) in all the regions of the district.

3.2. Base yields

The base yields (1980–2009) in the study location ranged between 1057 kg/ha and 1659 kg/ha showing spatial heterogeneity across the district. A spatial analysis of yield data across the four natural divisions revealed the highest yields in southern region followed by highlands, central and northern regions. Under the current climate, simulated groundnut yields vary by an order of annual rainfall amounts across the locations and soil types. In general, the southern region with comparatively higher rainfall, showed the highest crop yields. Pod yields were varied from 1199 kg/ha in Vertisols to 1509 kg/ha in Alfisols. Different genetic traits in the form of virtual cultivars and management options were simulated to quantify the impact of these technologies on baseline groundnut yields. The yield benefit observed due to 10% longer maturity cultivars was found to be very less (2%). However, substantial spatial variability was observed within the district with southern region found to be benefited with 7% increase and highland region with 2.6% increase in yields (Fig. 6). Increasing the duration of the baseline cultivar was not beneficial in the northern and central regions. Incorporating drought tolerance traits in the baseline cultivar showed an overall increase of 5% in yields and a 4.5–5.8% increase in yields, across the regions. Among the agronomic interventions simulated, providing one supplemental irrigation at 60 DAS showed significant improvement in groundnut yields across location ranging from 12.6 to 21.5% and an overall increase of 17%. The northern region benefited the most with one supplemental irrigation. The spatial maps on agronomic intervention of one supplemental irrigation generated for the district showed increased yields in almost all the places.

3.3. Climate change impacts on crop yields

Five GCMs were used to study the impact of climate change on groundnut yields under RCP 8.5 during Mid-century period. Table 1 shows the summary of the projected change (%) in groundnut yields between the baseline (1980–2009) and the Mid-century future climate (2040–69). Under climate change, groundnut yields declined in four of the five GCMs tested. Only GFDL-ESM2M GCM showed positive impact on yields. Pod yields decreased by 7.5%, 3.9%, 1.2%, and 0.2% with MIROC5, CCSM4, MPI-ESM-MR, and HadGEM2-ES respectively. GFDL-ESM2M GCM predicted a 6.1% increase in groundnut yields. The spatial analysis of climate change impacts on groundnut indicates that similar trends were observed in almost all the regions of Anantapur with a decline in yields with four GCMs and increase with one GCM (Fig. 7). However, while the northern region was found to be greatly benefited with climate change as predicted by GFDL-ESM2M and HadGEM2-ES, the southern region was found to be more vulnerable to it. The spatial maps of impacts of climate change also depict similar results for groundnut in Anantapur district.

3.4. Adaptation strategies

As an adaptation strategy to combat climate change impacts on groundnut, virtual cultivars by incorporating various desirable plant

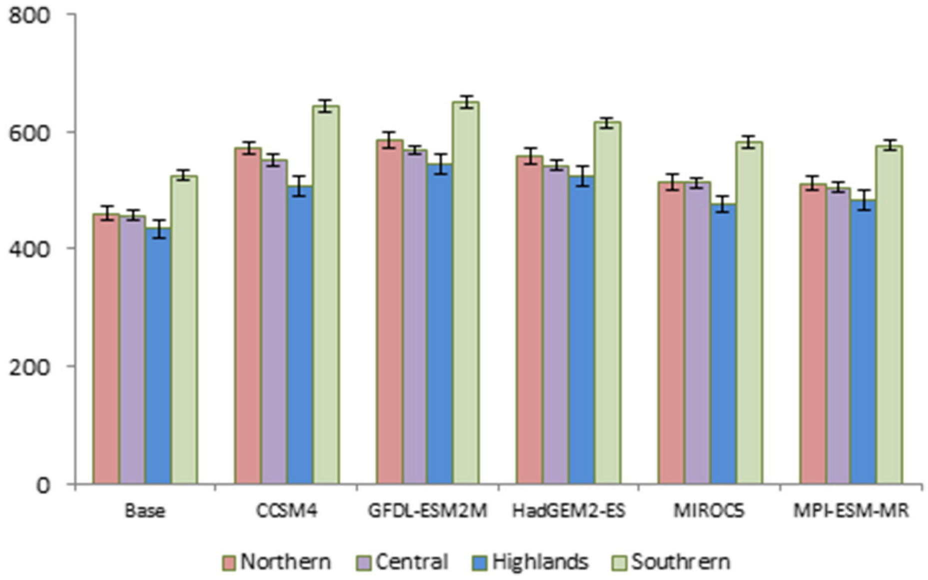


Fig. 4. GCM projected change in crop season rainfall (mm) during Mid-century period compared to the baseline in Anantapur. Bars indicate the standard error.

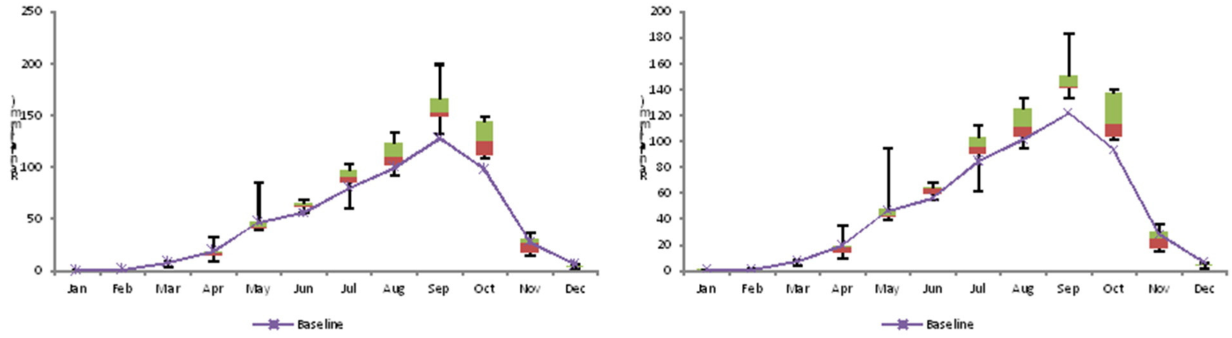
traits and agronomic management options were tried as an adaptation strategy. Virtual cultivar having heat, drought and 10% longer life cycle, management option such as supplemental irrigation at 60 DAS was simulated to study spatial variations in groundnut yields.

3.4.1. Cultivars with 10% longer life cycle

Simulations with longer life cycle cultivar under climate change conditions resulted in an overall positive response with an average 1.8% increase in yields across locations. However, this was more prevalent in the southern region where there was a 6.8% increase in groundnut yields while it was 2.1% in the highlands region compared to the baseline cultivar yields under climate change. This adaptation strategy was not beneficial in the central and northern regions as it resulted in a 0.4 and −0.8% reduction in groundnut yields respectively.

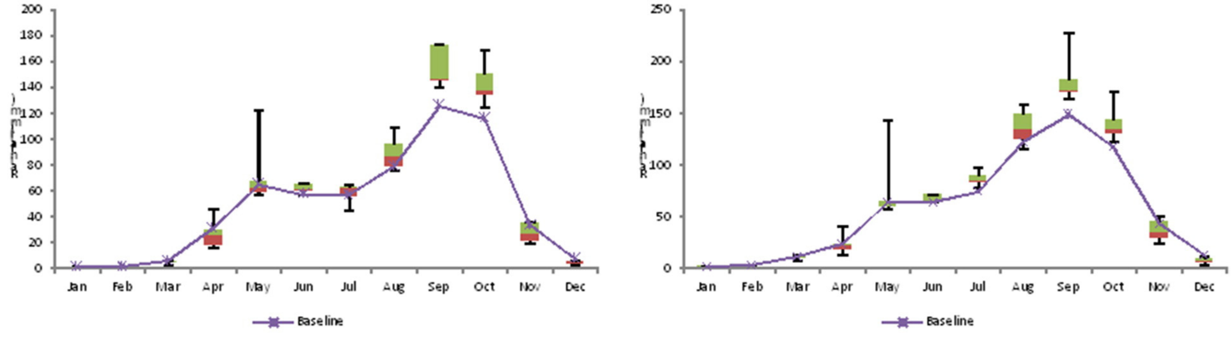
3.4.2. Drought tolerance

Incorporating drought tolerance traits into base cultivar resulted in significant yield improvements across locations in Anantapur. Yield



a) Northern Region

b) Central region



c) High land region

d) Southern region

Fig. 5. Box-plots of five GCMs projected changes in monthly rainfall (mm) during Mid-century period at four natural divisions of Anantapur.

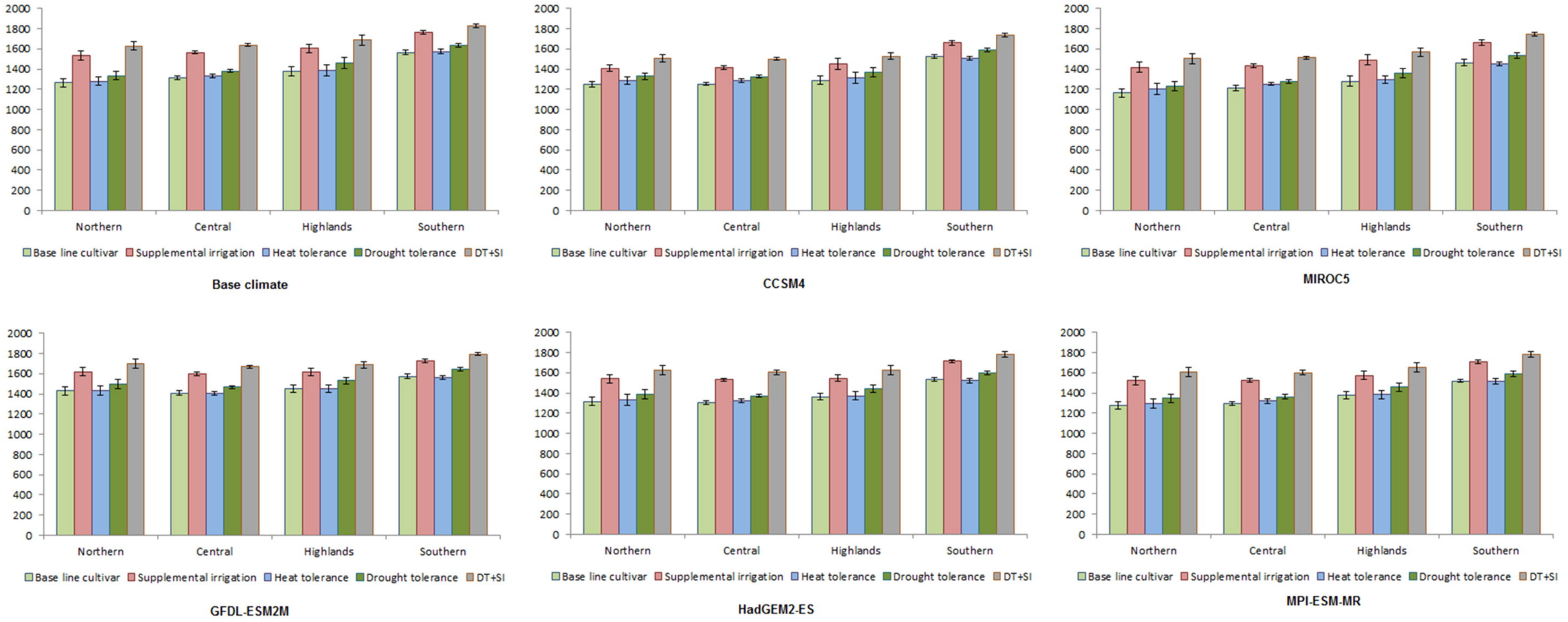


Fig. 6. Effect of heat, drought tolerant virtual cultivars and management options on groundnut yields (kg/ha) in Anantapur as projected by five GCMs compared to baseline. Bars indicate the standard error.

Table 1
The summary of climate change impacts on groundnut in four regions of Anantapur during Mid-century period.

Region	Base climate (1980–2009)	Climate change (2040–2069)											
		CCSM4		GFDL-ESM2M		HadGEM2-ES		MIROC5		MPI-ESM-MR		Average of 5 GCMs	
	Yield	Yield	% change	Yield	% change	Yield	% change	Yield	% change	Yield	% change	Yield	% change
Northern region	1264	1250	−1.1	1429	13.0	1318	4.2	1163	−8.0	1277	1.0	1287	1.8
Central region	1317	1253	−4.8	1408	6.9	1305	−0.9	1212	−8.0	1295	−1.6	1295	−1.7
Highland region	1380	1290	−6.5	1451	5.1	1362	−1.3	1278	−7.4	1374	−0.4	1351	−2.1
Southern region	1565	1524	−2.6	1573	0.5	1532	−2.1	1465	−6.4	1520	−2.9	1523	−2.7
Anantapur district	1381	1329	−3.8	1465	6.1	1379	−0.2	1279	−7.4	1366	−1.1	1364	−1.3

increases ranged from 4.5 to 6.0% with highland, central and northern regions found to benefit most compared to the southern region (Fig. 8).

3.4.3. Heat tolerance cultivar

Incorporating heat tolerance traits into baseline cultivar resulted in a meager increase in groundnut yields in Anantapur, ranging from 0.8% to 1.9%. The northern, central and highland regions showed positive response for heat tolerance and the southern region showed negative impact.

3.4.4. Supplemental irrigation

Supplemental irrigation was found to be one of the best agronomic adaptation strategies to increase groundnut yields significantly under climate change conditions. In all the five GCMs and regions tested the application of one irrigation at 60 DAS increased groundnut yield to the tune of 14.4% compared to the normal practice. A single supplemental irrigation was more beneficial in the northern and central regions with 16.8% and 15.9% improvement, respectively compared to that in the highland (13.7%) and southern regions (11.3%). The spatial maps generated on the impact of one supplemental irrigation on groundnut yields under climate change conditions as simulated with five GCMs showed increased yields at almost all the locations in Anantapur districts (Fig. 9).

Among the combination of adaptation options studied, a combination of drought tolerance traits and supplemental irrigation was found to be very effective in improving groundnut yields by 20% under climate change conditions compared to baseline cultivar under climate change. The northern and central regions benefited highly by this adaptation strategy leading to 23.6% and 21.9% increases respectively in yields followed by the highland and southern regions with 19.3 and 16.1% increases respectively.

4. Discussion

The present study attempted to develop a user-friendly decision support tool to quantify the potential impacts of future climate change on groundnut yields. The tool will provide useful insights essential to inform policies, prioritize research, reform crop management practices, and adjust the distribution of various adaptation options to reduce vulnerability in the future. The overall results clearly show the capabilities of CROPGRO-Peanut model to simulate groundnut yields under varying soil, climate and management conditions enabling us to simulate and analyze the impact of climate change and various adaptation options to mitigate its impacts. Despite considerable uncertainty relating to future climate change and its consequences (Challinor, 2011), this analysis is probably the first study that considers the impact of climate

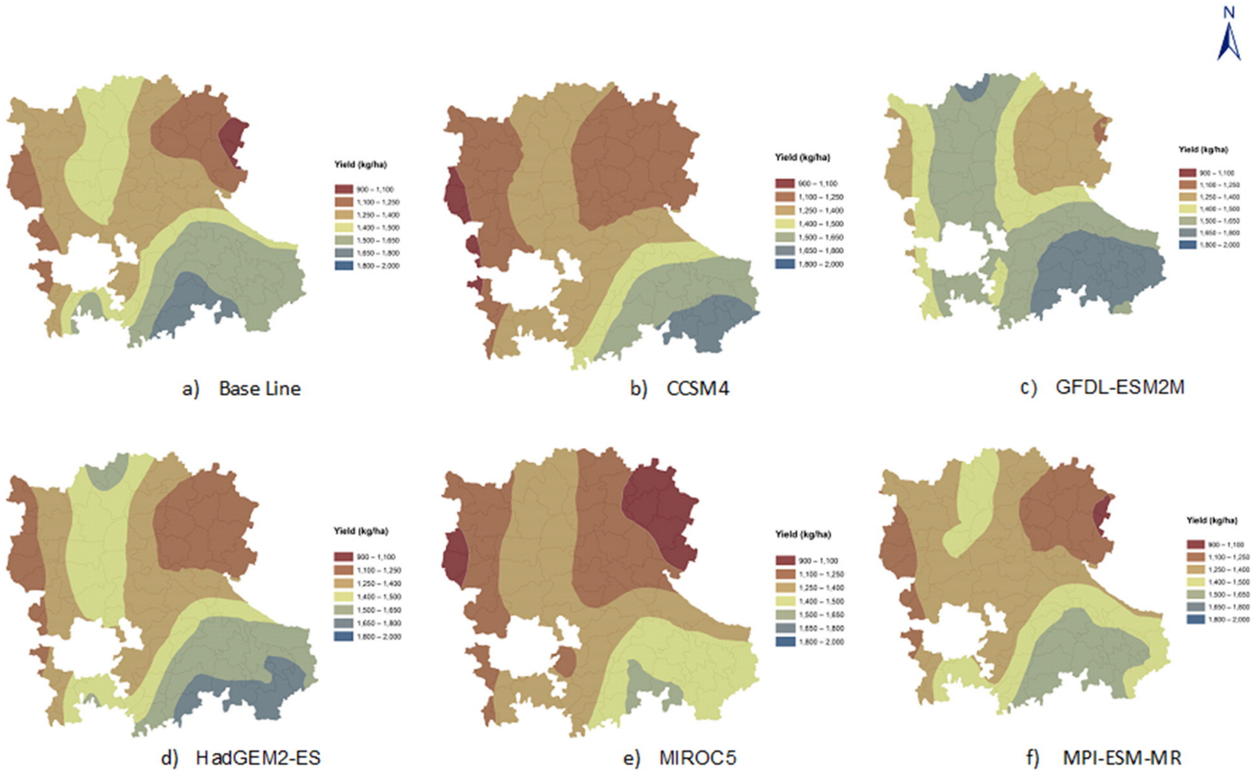


Fig. 7. Spatial distribution of groundnut yields as projected by five GCMs for Mid-century period under RCP 8.5 compared to the baseline.

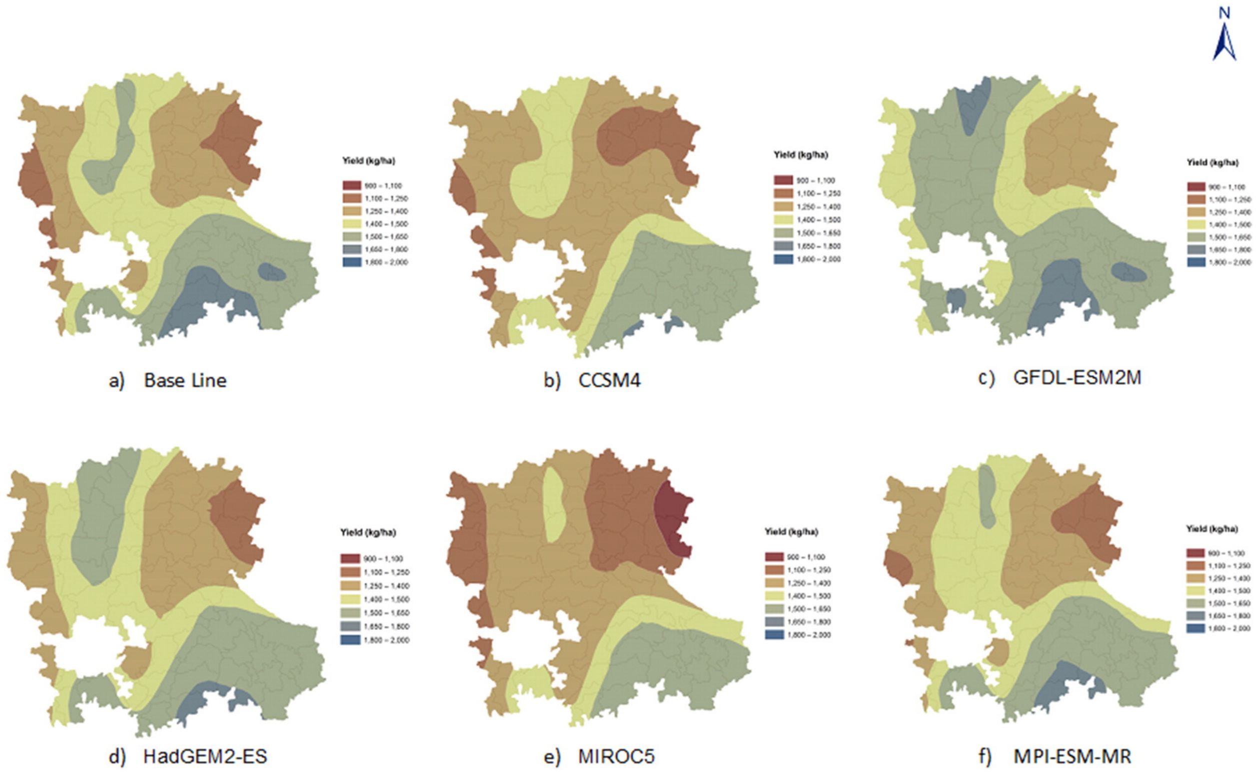


Fig. 8. Spatial distribution of groundnut yields as projected by five GCMs for mid-century period under RCP 8.5 compared to the baseline having drought tolerance trait.

change analysis using farm climate data in four different regions using six different soil types. Significant variation in the baseline yields can be attributed due to soils and rainfall. Regression analysis indicates that rainfall positively and significantly affects groundnut yields. Among different soils, Alfisols have highly positive and significant impact on crop yields. These simulation results confirm the earlier studies of Alfisols being best suited for groundnut cultivation and that rainfall is an important factor which controls yields in Anantapur (Bapuji Rao

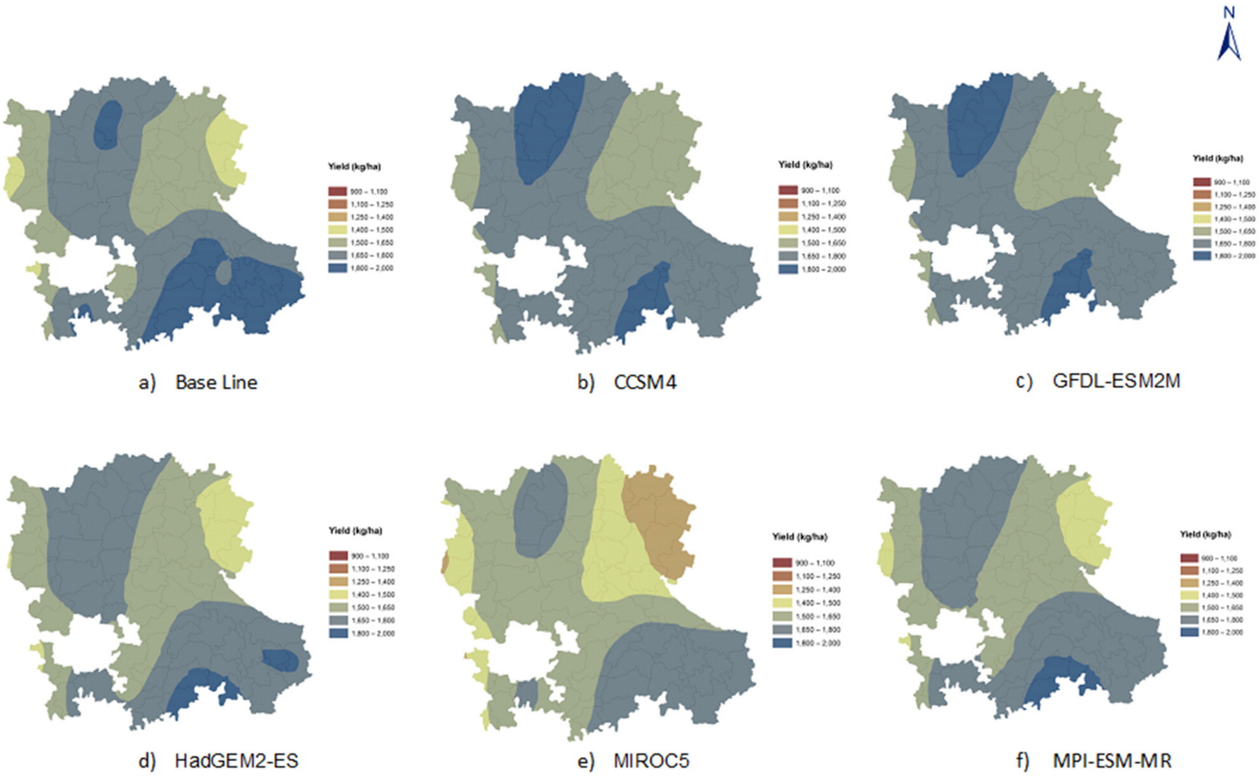


Fig. 9. Spatial distribution of groundnut yields as projected by five GCMs for mid-century period under RCP 8.5 compared to the baseline receiving supplemental irrigation at 60 DAS.

et al., 2011). Analysis of five GCMs demonstrated that there is considerable increase in rainfall activity in the range of 10.6 to 25% by Mid-century period (2040–69) under RCP 8.5. Among the various regions studied, greater activity was observed in the northern region which resulted in a marginal increase in groundnut yields even under increased maximum and minimum temperatures. Further analysis of rainfall distribution indicated an increase in rainfall in September and October in almost all GCMs. However, there was slight decrease in rainfall in November which coincided with pod filling and led to a slight decrease in pod yields. The variation in crop yields among the different locations is mainly because of variations in the soil type, rainfall and temperatures which affect various daily biochemical processes in the plant. The main reason for reduced yields in the simulations during Mid-century period was to the effect of higher temperature leading to an acceleration of the phenological cycle and finally reduction in yields. A large variation was found across soil types under both current and future climate conditions, implying groundnut sensitivity to soil types.

4.1. Determination of adaptation options

The impacts of climate change on groundnut can be quantified effectively using simulation modeling studies; we can also study the extent to which the impacts can be avoided through various adaptation options. Different management scenarios were studied using baseline climate data, shifting planting dates in order to prevent the critical stages of crop development coinciding with the extreme high-temperature period. However, this didn't result in improved yields as delayed sowing led to crop exposure to moisture stress during the critical pod filling stage. Other agronomic options such as critical irrigation have proved highly beneficial as the model simulations of rainfed groundnut indicates that the crop experienced water stress during pod filling stage and providing one irrigation during pod filling stage was found to increase yields in almost all the regions both under baseline and future climate situations.

Incorporating various promising traits such as drought and heat tolerance and a longer life cycle in groundnut was found beneficial in improving groundnut yields under climate change conditions. Groundnut requires an optimum temperature range of 25–30 °C for vegetative development (Williams and Boote, 1995; Weiss, 2000) and 35 °C for flower appearance and pegging (Prasad et al., 2003). As per future climate projections, daily temperatures may exceed optimum temperature and even some times record more than critical temperatures during the groundnut growing period, inhibiting crop development and productivity. High temperatures delay pegging and podding and lead to reduction in yield. Thus developing virtual cultivars with high temperature tolerance and high thermal requirements may lead to their effective use of the growing season to capitalize on the high CO_2 fertilization effects due to climate change and produce higher yields.

When a groundnut crop is exposed to drought conditions during crop growth period, it affects leaf expansion and photosynthesis and pod filling period affects shelling percentage (Clifford et al., 1993). Cultivars having drought tolerance traits will have better root characters such as increased root length density that enhances plant water use by increasing the depth of effective water extraction (Singh et al., 2012). This was clearly evident from this study as cultivar with drought tolerance produced 4.5–6.0% higher yields across various locations in Anantapur. The benefits from incorporating drought tolerance traits are much higher than those from heat tolerance traits, mainly because incorporating heat tolerance traits might have resulted in faster crop senescence with increased sink demand for assimilates leading to poor filling of seeds due to other yield limiting conditions (Singh et al., 2014a,b). Thus, in future climate change conditions of increased temperatures and varying duration of water availability, cultivars that can withstand high temperatures and drought conditions will be able to take advantage of increased CO_2 fertilization and produce more yields.

5. Conclusions

This study developed and tested a tool for investigating the spatial implications of climate change on groundnut production in Anantapur district. The CROPGRO-Peanut model that has been calibrated and validated for many groundnut growing regions of the world was used to study the spatial responses to various genetic and agronomic management practices under both baseline and climate change scenarios by using GIS and crop model based interface. The methodology presented here was found to be reassuring because it provides a common ground for breeders, plant physiologist, crop modelers and GIS users to discuss simulation results and further potential research directions. Simulated crop yield and other maps generated under different management scenarios can be used to better communicate model predictions to various stakeholders. Further, the methodology developed can be used for spatial modeling of crop productivity for any crop in any region or country. The output of this methodology can aid scientists in prioritizing research and decision makers to understand the extent and status of climate change and its potential impacts on the productivity of various crops.

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Disclaimer

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