Impact of climate change on kidney bean (Phaseolus vulgaris L.) in India and Kenya

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Research Article

Keywords: Simulation, modelling, climate change, impacts, Phaseolus vulgaris L.

Posted Date: June 3rd, 2022

DOI: https://doi.org/10.21203/rs.3.rs-1616105/v1

Abstract

Climate change is significantly challenging food production and nutritional security. Gaining an understanding on the impacts of climate change on various crops enables us to develop adaptation and mitigation strategies to sustain yields in future climates. Kidney bean, one of the major pulses in the world, is a rich source of protein and is a part of daily diet for over 300 million people. InfoCrop- kidney bean dynamic simulation model was applied to simulate the impact climate change on seed yield in India and Kenya in 2020, 2050 and 2080 climate scenarios under representation concentration pathways 4.5 and 8.5 of Coordinated Regional Downscaling Experiment Regional Climate Models. Without adaptation in India, kidney bean seed yield is projected to reduce (4-60%) in 5 out of 10 locations depending on scenario. In other locations, impacts are dependent on the relative change in rainfall and temperatures in different climate scenarios. In case of Kenya, during March-May season, seed yield variation is projected to be more, depending on location and climate scenario. During the October-December season, kidney bean seed yield is projected to reduce up to 60% in majority of locations. Additionally, inter-annual variation in seed yield is projected to increase for most of the locations in India and Kenya. Projected decline in seed yield is mainly attributed to a decrease in rainfall and increased variability in rainfall and temperature. Adaptation options such as shifting the sowing time, provision of supplementary irrigation and improved varieties may help to sustain yield in future climates.

1 Introduction

The concentration of atmospheric greenhouse gases has increased by approximately 50 per cent within the last 200 years leading to the well-known phenomena of global warming, with each decade becoming warmer than the preceding period (Ochieng *et al.*, 2016). IPCC assessment report indicates that most regions of the world will experience an increase in average surface air temperatures, water scarcity accompanied by desertification and periods of extreme & unpredictable precipitation (IPCC, 2021), particularly in tropical regions such as India and Kenya.

In India, during 1901-2018 the annual mean surface air temperature has increased by about 0.7 °C (Srivastava et al. 2019). The summer monsoon precipitation has shown a declining trend since 1950 (Kulkarni 2012). The climate change scenarios over India, derived from 32-global climate model (GCMs) ensemble, project an increase in minimum temperatures in the range of 0.95-4.07°C in 2020 to 2080 scenarios over baseline (1976-2005) period in ‘Kharif’ (June-September) season; and in the range of 1.1-4.65°C in ‘Rabi’ (October-March) season. Maximum temperatures are projected to increase by 0.74-3.53°C (2020 to 2080) during ‘Kharif’ and by 0.88-4.01°C in ‘Rabi’ (Naresh Kumar *et al.*, 2019). In case of Kenya, since 1960, the mean annual temperatures have increased by 1°Cat an average rate of 0.2°C per decade. Climate projections indicate an increase in temperatures by 1.8°C and 2.4-2.8°C for 2020 and 2050 scenarios respectively. Precipitation during the March-May (long-rains) season is expected to decrease by 10%. However, during October-December (short-rains) season precipitation is projected to increase by 8-10% and extend into the hot and dry months of January and February, for most parts of the country (Parry *et al.*, 2012; Kariuki, 2016).

Cultivation of kidney bean in India has gained traction over the years due to increased awareness of the crop's nutritional value and good market prices. The crop is cultivated on an estimated area of 90,000 ha. The national average yield ranges from 421-1,000 kg ha^{-1} (Gupta et al., 2019). Kenya is the second-largest producer of kidney bean in East Africa. In 2019, production was estimated at 0.74 Mt obtained from cultivation on an area of about 1.16 Mha. The national average productivity is estimated at 640 kg ha^{-1} (FAOSTAT, 2021). However, the average yield for most varieties ranges from 1.4-1.7 t ha^{-1} with proper management practices (KALRO, 2008; Mwangi *et al.*, 2019). Overall, the national average productivity of kidney bean in India and Kenya is relatively low compared to the international average ranging from 1,500-2,000 kg ha^{-1} (Gupta *et al.*, 2019). These yield gaps are expected to worsen due to projected temperature and rainfall variation in future climate scenarios which may affect kidney bean growing area suitability. Additionally, projected changes in seasonal rainfall amount and distribution may lead to limited availability of water for crop production which may lead to further negative shocks on yield.

The use of empirical and process-based models in assessing climate change impacts on crop production has been instrumental in guiding policymaking and developing strategies for climate change adaptation and mitigation (Hodson & White, 2010). Crop modelling is widely applied for assessing the performance of agricultural systems under projected climate change scenarios along with the outcomes of potential food system shocks (Reynolds *et al.*, 2018)**.** Crop models are developed by integrating different modules for various processes responsible for crop growth. Some of these modules include; crop growth and development, source-sink balance, soil water balance, soil nitrogen balance, soil organic carbon dynamic, crop-pest interactions and emissions of greenhouse gases (Aggarwal *et al.*, 2006; Oteng-darko *et al.*, 2013).

Extensive research has been carried out to assess the impacts of climate change on crops such as maize (Abera *et al.*, 2018; Byjesh *et al.*, 2010; Charles *et al.*, 2017; Kogo *et al.*, 2019; Lin *et al.*, 2015), wheat (Naresh Kumar *et al.*, 2014; Zacharias *et al.*, 2014), rice (Naresh Kumar *et al.*, 2013), potato (Adavi *et al.*, 2018) and coconut (Naresh Kumar & Aggarwal, 2013) in India. However, limited studies have applied crop simulation modelling in identifying potential impacts of climate change on kidney bean production in India or in Kenya. This is despite findings from some studies showing that majority of current kidney bean growing areas in South America and Sub-Saharan Africa will become unsuitable for cultivation of the crop by the year 2050 due to drought and heat stress associated with climate change (Carlos et al., 2020; Ochieng et al., 2016). DSSAT, APSIM and Aquacrop have been applied in simulating kidney bean growth and development in various regions of the world (de Oliveira *et al.*, 2012; Fereres *et al.*, 2017; Lado *et al.*, 2017). However, most of these studies did not go further to assess climate change impacts on the crop.

In this study InfoCrop v2.1, a dynamic simulation model for kidney bean that better represents the crop's response to tropical conditions, developed at the Centre for Environment Science and Climate Resilient Agriculture, India Agricultural Research Institute, New Delhi, India (Aggarwal et al., 2006; Naresh Kumar et al., 2014a & 2015) is calibrated and validated for kidney bean. The model was then applied to assess the impact of climate change on kidney bean yield in selected locations in India and Kenya.

2 Materials And Methods

The kidney bean simulation module in InfoCrop v2.1 generic model, used in this study, was developed at the Environmental Modelling lab of the Centre for Environment Science and Climate Resilient Agriculture, ICAR-Indian Agricultural Research Institute (Naresh Kumar et al., unpublished). The model was designed to simulate the growth, development and yield of kidney bean in response to environmental factors such as soil, weather and management practices. The InfoCrop V2.1 generic model has the following crop growth and soil processes;

i. *Crop growth:* Phenology, radiation use, leaf area growth and senescence, dry matter production and partitioning, source and sink balance, nitrogen uptake and partitioning and effects of nitrogen, water, temperature and CO_2 on growth processes.
ii. *Soil water flow:* Root water uptake; water soil sub-surface movement, soil inter-layer movement, drainage, evaporation and runoff.
iii. *Soil nitrogen dynamics:* Mineralization, fixation, soil inter-layer movement, nitrification, denitrification, volatilization and leaching.
iv. *Soil carbon dynamics:* Mineralization and immobilization of soil organic matter.
v. *Environmental impact:* Temperature, water, flooding, nitrogen stresses

The input data for calibration of the model included data on daily weather, soil characteristics, varietal coefficients and crop management (Table 1).

2.2. Model calibration and validation

2.2.1. Calibration

For calibration of the model, a field experiment was conducted in January-April 2020, in the research farm of ICAR-Indian Agricultural Research Institute, New Delhi-110012, India. The experiment aimed to investigate the interactive effect of different irrigation and temperature regimes on the growth and yield attributes of kidney bean. The best performing treatment i.e. kidney bean grown in seasonal mean temperature of 24.2°C with irrigation provided at sowing, vegetative and pod-filling phase was selected for calibration. Additionally, the model was also calibrated for other treatments i.e. kidney bean grown in seasonal mean temperature of 19.6°C with irrigation provided at sowing and vegetative phase. To set up the model, preliminary varietal coefficients were obtained from published literature. To calibrate the model, data on soil characteristics; crop phenology, time-series LAI, total dry matter and its partitioning and seed yield; crop management practices and daily weather for selected treatments were used as model input. To simulate proper phenology, leaf area index (LAI), dry matter and seed yield, several iterations were done to closely match the observed with the simulated values.

The model was evaluated using statistical indicators i.e. root mean squared error (RMSE) (Fox, 1981); agreement index (AI) and model efficiency (ME) (Wallach et al., 2006). The formulae for these indicators are given below.

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(O_i - S_i)^2} \quad \text{(II)}$$

$$\mathrm{AI} = 1 - \left(\frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(|S_i - \bar{O}| + |O_i - \bar{O}|)^2}\right) \quad \text{(III)}$$

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{N}(O_i - S_i)^2}{\sum_{i=1}^{N}(O_i - \bar{S}_i)^2} \quad \text{(IV)}$$

Where n is the number of samples, S_i and O_i are the simulated and observed values respectively, $\bar{O}$ is the mean of the observed data, $\bar{S}$ is the mean of the simulated data. RMSE estimates the root mean square deviation between simulated and observed values. A higher RMSE value indicates low accuracy of the simulation. AI measures the agreement of the simulated values with observed values in terms of trend. Model efficiency measures the model's ability to match observed values.

The model had high accuracy in simulating the phenology of the crop in terms of days to 50% first flowering, days to physiological maturity with an error in the range of 2-5 days. The LAI was simulated with an R^2 of 0.81 and with a high AI of 0.93. Model efficiency in simulating LAI was (R2 =0.7) with an acceptable level of RMSE (0.55). Additionally, the model could closely simulate the dry matter production at different stages of crop growth as well as seed yield.

2.2.2. Validation

After satisfactory calibration of the kidney bean model, validation was done for remaining treatments along with data from published literature for other locations in India (Parbani, Pune and Anand) and Kenya (Eldoret, Machakos and Kabete). These treatments included different management conditions such as varieties, sowing dates, irrigation and nitrogen levels, apart from variations in soil and climate. A total of 87 treatments (Table 2) were used and the model was validated for phenology, total dry matter and seed yield.

The model performed well in simulating phenology, total dry matter and seed yield across different experiments (Fig 1). Statistical indicators for various parameters were as follows: days to 50% flowering (RMSE: 2 days, AI: 0.98, R^2: 0.94, ME: 0.93); days to 50% physiological maturity (RMSE: 3 days, AI: 0.99, R^2: 0.94 and ME: 0.99); total dry matter (RMSE: 487 kg ha^{-1}, AI: 0.99, R^2: 0.76 and ME: 0.96) and seed yield (RMSE:223 kg ha^{-1}, AI: 0.95, R^2: 0.8 and ME: 0.81). A high agreement index for all growth and yield parameters indicates the model's ability to capture the trend of the effects of different factors on the growth and development of kidney bean.

2.3. Climate change impact assessment

Climate change impact analysis was carried out for rainfed kidney bean production. Simulations were done for *'Kharif'* (July-September) season in India. However, Kenya experiences a bimodal rainfall regime distinguished as long rains season i.e. March-May (MAM) and short rains season i.e. October-December (OND). Thus, analysis was done for both seasons. High yielding, commonly grown, reference varieties were considered for the analysis i.e. Varun and KAT X56 for India and Kenya respectively. Selected locations in India were: Dahod (74.26°N 22.84°E), Nilgiri (76.5°N 11.42°E), Chickmagalur (75.77°N 13.32°E), Baghpat (77.22°N 28.95°E), Darjeeling (88.26°N 27.04°E), Patna (85.14°N 25.59°E), Jabalpur (79.97°N 23.19°E), Pune (73.86°N 18.52°E), Palani (77.52°N 10.45°E) and Amritsar (74.88°N 31.62°E) and in Kenya viz., Eldoret (0.53°N 35.28°E), Embu (-0.5°N 37.45°E), Kakamega (0.27°N 34.75°E), Kisii (-0.68°N 34.78°E), Kitale (1 °N 34.98°E), Machakos (-1.58°N 37.23°E), Makindu (-2.28°N 37.83°E), Meru (0.08°N 37.65°E), Nakuru (-0.27°N 36.1°E) and Nyeri (-0.43°N 36.97°E). These locations represented major kidney bean growing areas in India and Kenya. Common crop management practices followed by farmers along with general soil characteristics of the selected locations were taken into consideration.

2.3.1. Processing of baseline climate data and future climate projections

Location-wise weather data i.e. daily rainfall, maximum and minimum temperatures were required for simulating climate change impacts. Based on the availability of high-quality data, observed weather data were collected for the baseline period 1976-2005 (India) and 1982-2005 (Kenya) for each of the selected locations. These data were sourced from Indian Meteorological Department (IMD) and Kenya Meteorological Department (KMD).

Data on future climate scenarios (2010-2099) were obtained from the Coordinated Regional Downscaling Experiment (CORDEX) data portal. Two regional climate models (RCMs), common for India and Kenya were selected (Table 3). This study considered two representative concentration pathways (RCPs) i.e. RCP 4.5 and RCP 8.5 to represent mid and high-level emission pathways, respectively. RCM data were bias-corrected using the scaling method and ensembles were created to run simulations for different climate change scenarios i.e. 2020 (2010-2039), 2050 (2040-2069) and 2080 (2070-2099). For the baseline period, CO_2 concentration was set as 360 ppm, while under RCP 4.5 projected values of 422 ppm (2020 scenario), 495 ppm (2050 scenario) & 532 ppm (2080 scenario) were used. Under RCP 8.5, projected CO_2 concentration of 432 ppm (2020), 572 ppm (2050) and 799 ppm (2080) were used.

2.3.2. Estimating yield for baseline period and future climate scenarios

Data on daily weather, sowing time (according to season), varietal coefficients of reference variety, soil characteristics, crop management and CO_2 concentration were input into the model to simulate kidney bean seed yield for baseline period i.e. 1976-2005 (India) and 1982-2005 (Kenya). The mean of the yields from these years was taken as 'baseline yield'. Similarly, simulations were done for climate change scenarios (2020, 2050 and 2080) under different RCPs. The mean of 30 years yield under each scenario for each RCP was taken as 'mean yield in scenario'.

Climate change impact on seed yield, expressed as per cent change from mean baseline yield, was calculated as:

$$\text{Impact}=\frac{[(\text{Mean yield in scenario}-\text{Mean yield in baseline})*100]}{\text{Mean yield in baseline}}$$

3 Results And Discussion

3.1. Projected seasonal rainfall, maximum and minimum temperature

3.1.1. India

The mean total rainfall for the crop season ranged from 110-1335 mm for the baseline period across the locations. Climate change is projected to reduce rainfall significantly in these locations. Overall, rainfall is projected to decrease under all scenarios and RCPs with the highest decrease projected for Darjeeling location under RCP 4.5 (Fig 2a). The reduction is generally more in RCP 4.5 as compared to RCP 8.5 particularly up to 2050 scenario. Among the locations, mean seasonal maximum (T_{max}) and minimum (T_{min}) temperatures during the baseline period ranged from 24.7-39.8°C and 19.9-29.8°C, respectively. T_{max} is projected to increase by 0.7-3.5°C under RCP 4.5 and 1.7-3.9°C under RCP 8.5 in all locations except at Darjeeling, Palani and Nilgiri where it is projected to decrease (Fig 2b). Similarly, T_{min} is projected to increase by 0.9-3.6°C in all locations while a decrease of about 0.5-2.1°C is projected for Darjeeling, Palani and Nilgiri (Fig 2c).

3.1.2. Kenya

During the March-May season, seasonal rainfall is projected to decrease from the baseline (145-544 mm) under RCP 4.5 and RCP 8.5 across all scenarios, in most of the locations (Fig 2d). Seasonal maximum (23.8-33°C) and minimum (12.1-20°C) temperatures are projected to increase by 0.5-2.6°C and 0.3-2.3°C respectively, across all scenarios in the different locations. However, in 2050 scenario under RCP 4.5 T_{max} is projected to decrease by 0.7-1.3°C across all locations except at Kisii. Similarly, T_{min} is projected to decrease by 0.9-1.1°C in Embu and Makindu (Fig 2e and 2f).

Climate change analysis for the October-December season showed that seasonal total rainfall for the baseline period ranged from 203-506 mm and is projected to decrease in 2020 scenarios for most locations under both RCPs (Fig 2g). Similarly, a decrease is projected for 2050 and 2080 scenarios at all locations except Eldoret, Kitale, Kakamega, Kisii and Nakuru which are projected to experience a slight increase in rainfall. Temperatures during the baseline period ranged from 23.8-33°C (T_{max}) and 11.5-20.6°C (T_{min}) across different locations. Maximum and minimum temperatures are projected to increase in all scenarios and RCPs by about 0.7-3.8°C and 0.8-3.4°C, respectively (Fig 2h and 2i).

3.2. Impact of climate change on kidney bean seed yield

3.2.1. Seed yield deviation and inter-annual variability for locations in India

Seed yield in Patna, Darjeeling, Amritsar, Chickmagalur and Nilgiri is projected to decrease by 15-31%, 58-60%, 49-60%, 4-21% and 26-44% respectively across all scenarios and RCPs (Fig 3). The projected decrease in seed yield may be attributed to a reduction in total rainfall by about 14-57% under RCP 4.5 and 15-67% under RCP 8.5. In locations such as Patna and Amritsar, reduction in seed yield may be further attributed to the projected increase in maximum and minimum temperature by 1.8-3.9°C and 0.2-3.6°C respectively over baseline period temperature i.e. 33.8/25.7°C (Patna) and 34.5/24.1°C (Amritsar). This projected increased temperature may significantly exceed optimum temperatures (14-27°C) required for optimum kidney bean growth (Kakon et al., 2019).

In Jabalpur, yield is projected to decrease by 14-23% in all scenarios under RCP 4.5 while an increase of about 18-35% is projected under RCP 8.5. The reverse is observed in Pune where yield is projected to increase under RCP 4.5 and decrease in all scenarios under RCP 8.5. The opposing trend in seed yield deviation under different RCPs may be attributed to less reduction in rainfall (15-33%) under RCP 8.5 compared to that in RCP 4.5 (40-52% reduction) in Jabalpur. The reverse is observed for Pune, where the reduction in rainfall under RCP 4.5 is projected to be less (24-28%) than under RCP 8.5 (22-47%).

Mean seed yield deviation from the baseline period in Dahod and Baghpat varied across different climate change scenarios. In Dahod, yield is projected to decrease by 13% in 2020 and 2050 scenarios under RCP 4.5 and by 22% in 2020 scenario under RCP 8.5, while an increase is projected in 2080 scenario under both RCPs. In Baghpat, seed yield is projected to decrease by 60% and 12 % in 2020 & 2080 scenario under RCP 4.5 while an increase of 9% and 22% is projected for 2050 and 2080 scenario, respectively, under RCP 8.5.

Inter-annual variation in seed yield is projected to increase when compared to the baseline period in most locations and across all scenarios. However, in Palani inter-annual variation is projected to decrease in 2020 and 2080 climate scenarios under RCP 4.5 and 2020 and 2050 climate scenarios under RCP 8.5. Also, in Nilgiri inter-annual variation decreases from 40.4% in baseline to about 16% in all scenarios except in 2080 under RCP 8.5. In Baghpat, inter-annual variation projected to remain relatively the same (58-60%) in all scenarios.

3.2.1. Seed yield deviation and inter-annual variability for locations in Kenya

Simulations for the March-May season indicated that seed yield is projected to increase by 8-28% in Embu across different climate scenarios under RCP 4.5 and RCP 8.5. A similar trend is projected for Nyeri where yield is projected to increase by 2%-27% under RCP 4.5 and by about 14-53% under RCP 8.5. The reverse is projected for Kakamega, Kisii and Meru locations where seed yield is projected to decrease by 24-60% under different RCPs. In Eldoret, Kitale and Nakuru, seed yield is projected to decrease (4-28%) in 2020 scenario while an increase in yield is projected for 2050 (8-44%) and 2080 (7-52%) scenario under both RCPs. In Makindu and Machakos, yield is projected to decrease by 6-38% in 2020 and 2050 scenario while in 2080 scenario seed yield is projected to increase by 4-11% under RCP 4.5 and 26-30% under RCP 8.5 (Fig 4). Inter-annual variation in seed yield is projected to increase in all locations except at Eldoret and Nakuru where it is projected to decrease in 2050 and 2080 climate scenarios.

During the October-December season, seed yield is projected to decrease by 41-59%, 54-60% and 22-42% for Kakamega, Kisii and Meru across all scenarios under different RCPs (Fig 5). A reverse trend was observed for Eldoret, Embu, Nakuru, Nyeri and Makindu locations where seed yield is projected to increase by 5-60% across the scenarios and RCPs. In Machakos, seed yield is projected to decrease by 34% and 21% in 2050 scenarios under RCP 4.5 and RCP 8.5 respectively while an increase of 5-34% is projected for

2020 and 2080 scenarios. In Kitale, seed yield is projected to decrease by 2-29% in 2020 and 2080 scenarios. Inter-annual variation in seed yield is projected to increase compared to the baseline period in Machakos, Kisii, Meru and Makindu while for Eldoret and Nyeri locations a decreasing trend is projected for all scenarios under the different RCPs. In Embu, inter-annual variation in seed yield is projected to increase in 2080 scenario under both RCPs. For Kitale and Nakuru locations, inter-annual variation in seed yield is projected to increase in 2020 and 2080 scenarios. In Kakamega, an increase in the inter-annual variation in seed yield is projected for all scenarios except for 2020 climate scenario under RCP 4.5.

Overall, climate change impact analysis for March-May and October-December seasons show that reduction in rainfall is projected to be more during MAM season compared to OND season. Furthermore, locations such as Eldoret and Kitale may experience an increase in rainfall during the OND season. Despite the projected increase in CO_2 concentration, rise in temperature and reduction in rainfall may lead to decreased seed yield in all scenarios for Kakamega, Kisii and Meru during both seasons. During the OND season, where the reduction in rainfall is projected to be less than 15%, seed yield is projected to increase in Nakuru and Eldoret as opposed to MAM season where projected seed yield decreases when rainfall is projected to decrease by 40-52% under both RCPs. For some locations i.e. Embu and Nyeri, seed yield is projected to increase in all scenarios during both seasons. In most of the locations except Eldoret, Embu and Nyeri, inter-annual variation in seed yield is projected to increase when compared to the baseline period, in all scenarios during both seasons.

The relative impact of rainfall and temperature deviation in future climate scenarios are dependent on the baseline conditions. Though kidney bean responds positively to increasing atmospheric CO_2, the balance between temperatures and rainfall amount and distribution are projected to significantly influence the yield. However, kidney bean is moderately tolerant to high temperatures when sufficient moisture is available for growth. Minimum rainfall requirement for proper growth ranges from 300-600 mm (Webber et al., 2006). Findings from this study indicate that reduction in rainfall and increased variability are the main factors determining the decline in projected seed yield. Coupled with an increasing trend in mean maximum and minimum temperature, kidney bean cultivation in the locations considered in this study may experience substantial negative shocks.

4 Conclusion

Despite the projected increase in CO_2 concentration in future climate scenarios, cultivation of kidney bean in most of the growing areas in India and Kenya is expected to be negatively affected by the projected reduction in rainfall and increased variation, coupled with a projected increase in maximum and minimum temperatures. Though kidney bean can benefit from increased CO_2 concentration, yield is projected to be dependent on the relative effect of changes in rainfall and temperature and their variability. Adaptation measures such as shifting of the sowing time, provision of supplemental irrigation, and selection of drought and heat resistant varieties may enable farmers in India and Kenya to improve overall productivity of kidney bean in future climate scenarios. This study is the first attempt in assessing climate change impacts on kidney bean yield in India and Kenya. Therefore, further research on climate change impacts on kidney bean production at a national or regional scale is needed to support decision-making and policy measures that can enhance farmers' resilience and adaptation capacity in future climate scenarios.

Declarations

Acknowledgements: The corresponding author thankfully acknowledge the funding by NICRA (National Innovations in Climate Resilient Agriculture), Indian Council of Agricultural Research, New Delhi and DST-MRDP project entitled 'Agricultural productivity in climate change scenarios: impacts and adaptation pathways (A National Facility for Capacity Building on Simulation Modeling in Agriculture) by the Department of Science and Technology, GoI and for support by the Post Graduate School, IARI to the first author.

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Tables

Table 1 Input data required to calibrate the kidney bean model

Data required	Description of input data for the model
Weather	Daily maximum and minimum air temperature, rainfall, wind speed, vapour pressure and soar radiation of the respective crop growth season year
Soil characteristics and fertility	Layer-wise (3 layers) soil profile physical and chemical properties including soil texture (clay, sand, silt), bulk density, moisture content at field capacity, permanent wilting point, saturation point, soil organic carbon, soil available N, P_2O_5 and K_2O
Crop management	Date of sowing, depth of planting, seed rate, fertilizer dose, frequency, type and time of application, amount, time and frequency of irrigation and application of organic matter
Cultivar	Thermal time from sowing to seedling emergence, seedling emergence to 50% flowering and 50% flowering to maturity, base temperatures for the phenological phases, maximum temperature, specific leaf area, leaf area growth rate, light interception extinction coefficient, radiation use efficiency, etc.

Table 2 Details of the experiments used for validation of the kidney bean model for different locations in India and Kenya

Location	Lat	Long	Year	T_{max} range (°C)	T_{min} range (°C)	Soil type	Experimental details	Crop variety	Number of treatments	Reference
New Delhi	28.64 N	77.16 E	2020	15-38	3.0-21.8	Sandy loam	Irrigation; Temperature	Chitra	14	Present study
Parbhani	19.25 N	76.80 E	2003-2004	27.3-33.9	8.6-20.1	Clayey	Irrigation; Variety	Arka Suvidha; Arka Komal; HUR-137; Varun	16	Shalikrao, 2004
Anand	22.54 N	72.97 E	2012-2013	25.9-33.4	8.9-15.7	Loamy sand	Irrigation; Nitrogen	Gujarat rajma-1	12	Parmar, 2014
Parbhani	19.25 N	76.80 E	2004-2005	26.2-36.4	8-17	Clayey	Irrigation;	HPR-35	4	Jukte, 2005
Pune	18.54 N	73.84 E	2011	27-40.2	9-24.7	Clayey	Variety; Sowing time	Phule suyash; Phule varun; Selection-1; Vaghya	16	Somnath, 2014
Pune	18.54 N	73.84 E	2005-2006	28.6-36.7	7.2-20.3	Clayey	Sowing date	Varun	5	Bansi, 2006
Parbhani	19.25 N	76.80 E	2005-2006	27.5-36.7	6.3-15.0	Clayey	Nitrogen	Akra Komal	2	Parmeshwar, 2006
Eldoret	0.28 N	35.33 E	2014	20.8-26.4	10.9-13.1	Sandy clay loam	Irrigation	-	4	Oteki, 2017
Katumani	1.58 S	37.24 E	2012-2013	23.2-26.7	12.9-16.4	Sandy loam	Irrigation	KAT X56	4	Sennhenn et al., 2017
Katumani	1.58 S	37.23 E	2012	23.2-26.7	12.9-16.4	Sandy loam	Variety; Irrigation	Awash 1; Awash Melka; Mexican 142	6	Munuve, 2015
Kabete	1.24 S	36.73 E	2009	20.6-25.6	9.3-12.0	Clayey	Sowing date; Nitrogen	Mwezi Moja	4	Mwangi, 2010

*Lat- Latitude; Lon- Longitude; T_{max}- Maximum temperature; T_{min}- Minimum temperature

Table 3 List of the CORDEX-RCMs used in this study.

RCM	Short name	Institute	Forcing	References
Rossby Center Regional Atmospheric Model	RAC4	SMHI (Sveriges Meteorologiska och Hydrologiska Institut), Sweden	CNRM-CM5	(Osima et al., 2018)
MPI Regional model	REMO	MPI (Max Planck Institute), Germany	CNRM-CM5	(Diatta et al., 2021) (Diatta et al., 2021)

Figures

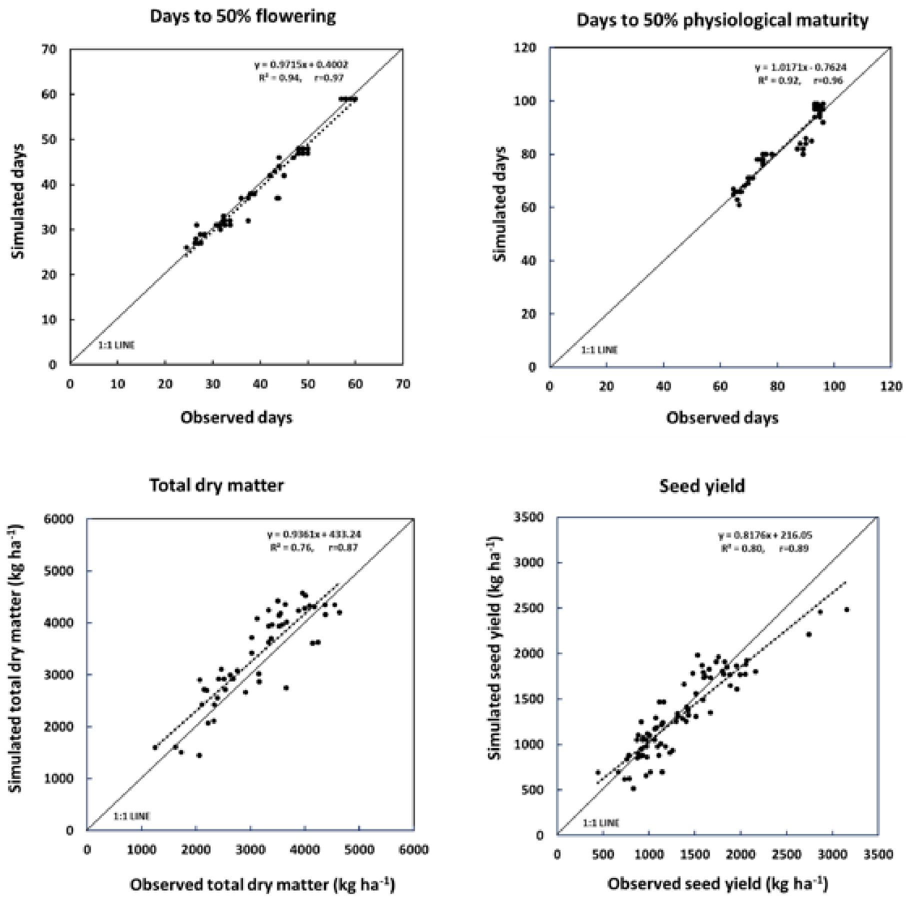

Figure 1

Validation results of the kidney bean model for days to 50% flowering, days to 50% physiological maturity, total dry matter and seed yield for different management conditions and locations in India and Kenya

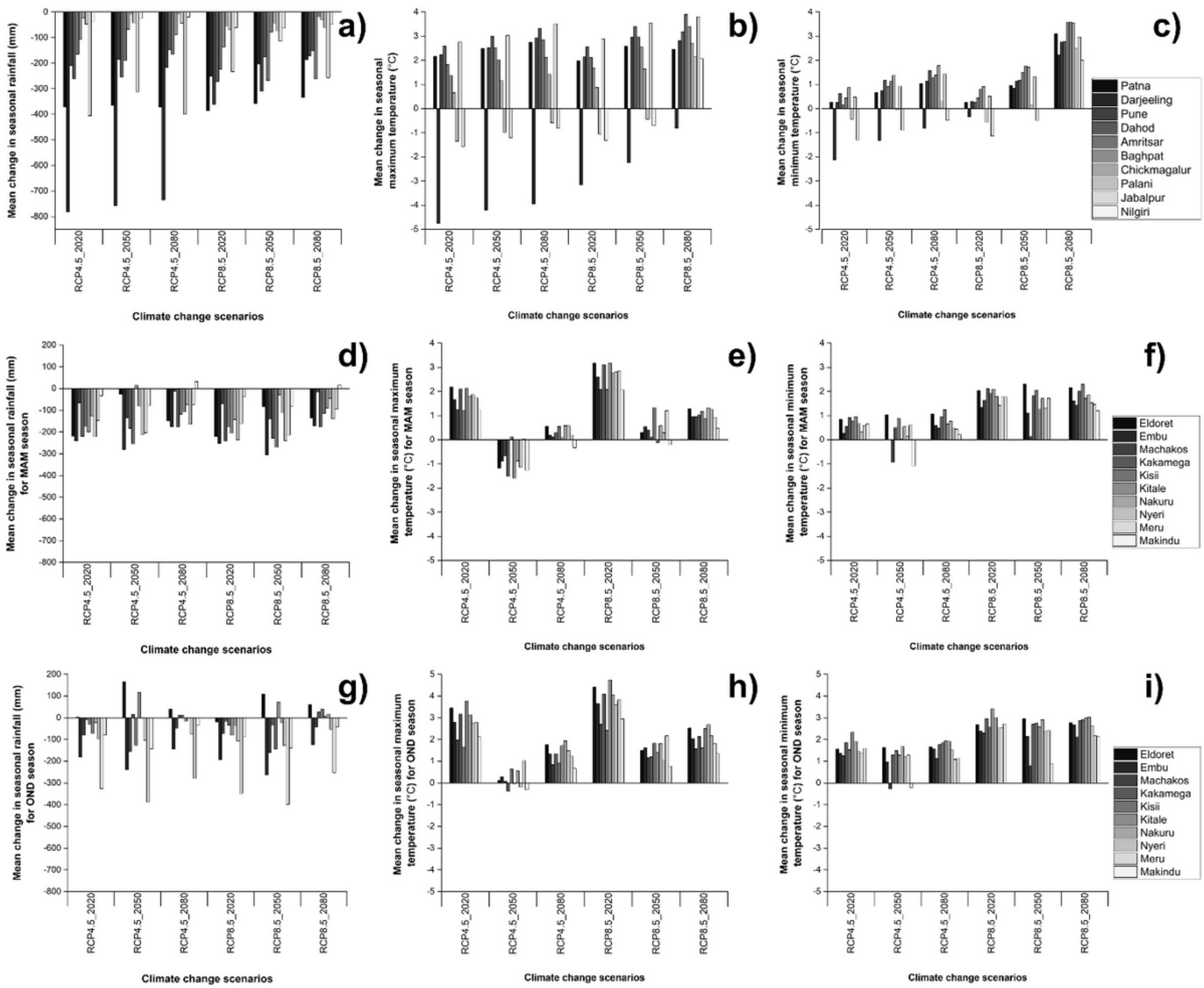

Figure 2

Mean change in seasonal rainfall, maximum and minimum temperature for different locations during a-c) June-September season-India), (d-f) March-May (MAM) season-Kenya and (g-i) October-December (OND) season-Kenya

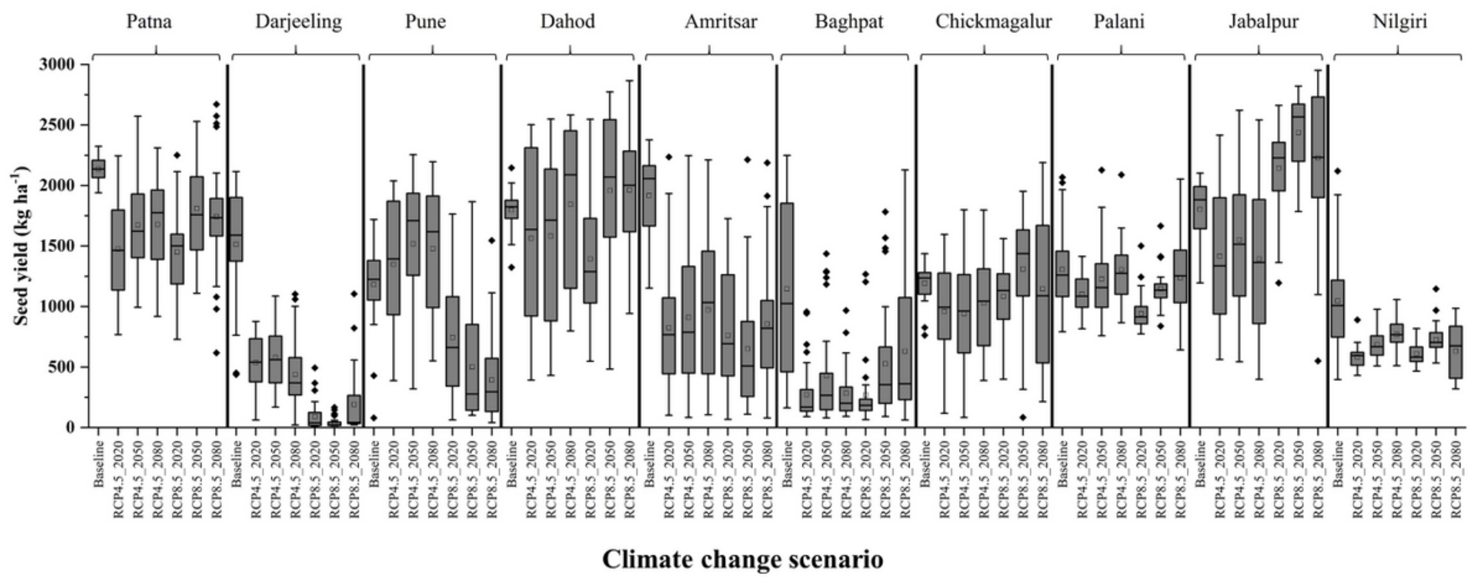

Figure 3

Simulated seed yield of kidney bean for the baseline period and different climate change scenarios under RCP4.5 and RCP8.5 for different locations in India

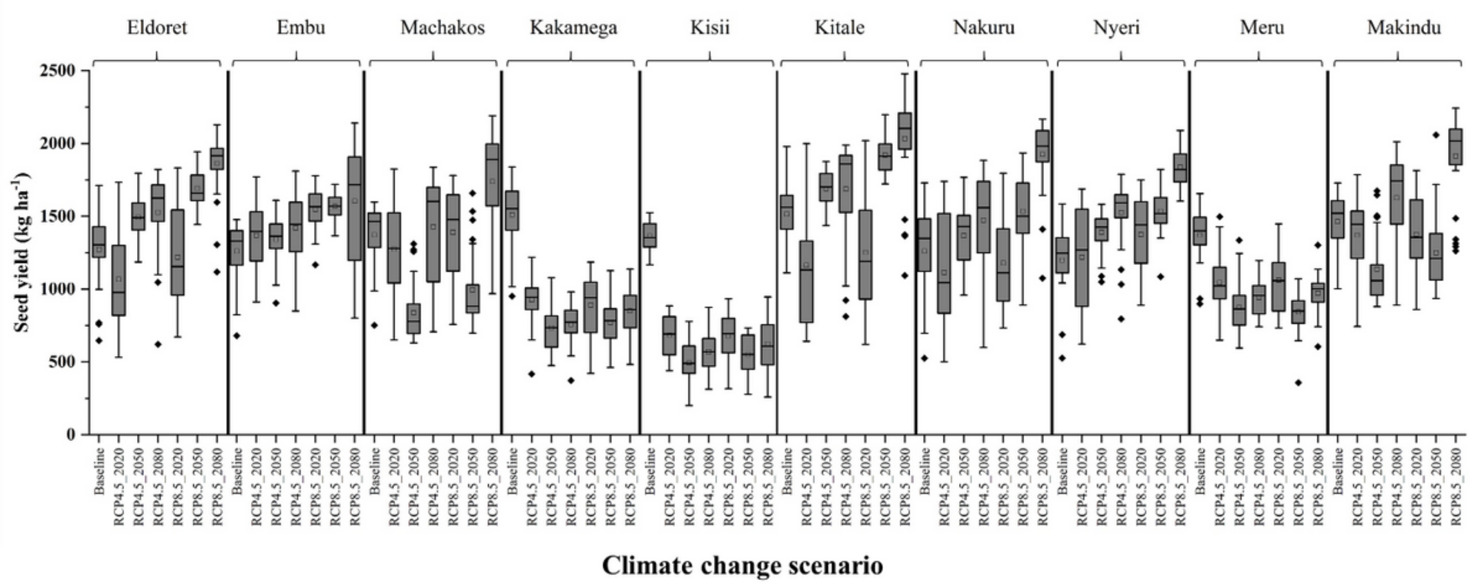

Figure 4

Simulated seed yield of kidney bean for the baseline period and different climate change scenarios under RCP4.5 and RCP8.5 in different locations in Kenya during March-May season

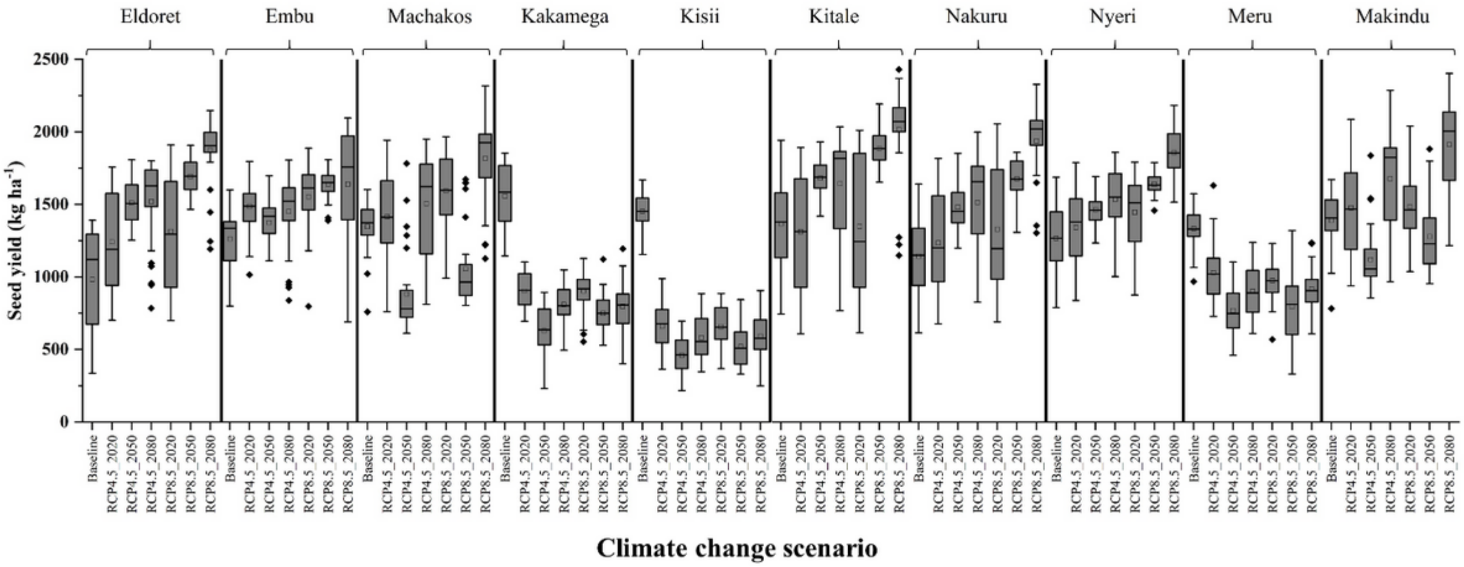

Figure 5

Simulated seed yield of kidney bean for the baseline period and different climate change scenarios under RCP4.5 and RCP8.5 in different locations in Kenya during October-December season