



Projected changes in mean temperature and total precipitation and climate suitability of cassava (*Manihot esculenta*) in major growing environments of India

SABITHA SOMAN¹, G BYJU² and J SREEKUMAR³

ICAR-Central Tuber Crops Research Institute, Sreekariyam, Thiruvananthapuram, Kerala 695 017

Received: 29 September 2015; Accepted: 13 November 2015

ABSTRACT

Cassava (*Manihot esculenta* Crantz) is an important food crop of India cultivated in an area of 228 000 ha for food, feed and fuel, contributes to food security, equity, poverty alleviation and environmental protection. This study examined the projected climatic changes in the major cassava growing environments of India and also calibrated and evaluated the EcoCrop model to study the impact of 2030 climate on cassava climate suitability in the major growing environments of India. The current climate and future climate projections of 22 GCMs from the SRES-A1B emission scenario were used for the study. The projected change in annual mean temperature and total annual precipitation in the major growing areas ranged from 0.9 to 1.2°C and from 6.8 to 112.4 mm, respectively. The calibrated data were used to drive the EcoCrop model to find out the suitability of current and future climatic conditions. The change in suitability for all the 22 GCMs used was calculated on pixel basis and the mean suitability change indicate that cassava is actually positively impacted in the current growing areas of India with -2.2 to 15% changes in climate suitability. This study concluded that cassava is potentially highly resilient to future climatic changes and it can become a future crop in India, where other crops would fail due to climate change.

Key words: Cassava, Current climate, DivaGIS, EcoCrop, Future climate, Global circulation models

Agricultural production could suffer progressive yield losses in the next hundred years due to climate change (IPCC 2007, Challinor *et al.* 2009). Many studies have predicted significant impacts from climate change for Indian agriculture (Aggarwal 2007, Swaminathan and Kesavan 2012 and Senapati *et al.* 2013). Cassava (*Manihot esculenta* Crantz) is the most important tuberous root crop and fourth most important source of food calories in the tropics and is a staple for more than 800 million people (Cock 1985 and Nasser *et al.* 2007). In Kerala, India, cassava is consumed as a secondary staple along with the staple, rice, and many rural poor consume it as the staple in different forms of preparations. Approximately 300 000 tonnes of sago and starch are manufactured from cassava tuberous roots by nearly 1 100 factories in Tamil Nadu and 50 factories in Andhra Pradesh state in India. Out of the total area of 228 000 ha under cassava in India, about 86% (195 990 ha) is in these three southern states (www.indiastat.org).

There are different studies which have focused on the impacts of climate change on different crops like rice, wheat,

maize (Chao *et al.* 2014 and Abdul Haris *et al.* 2013) and also on the impact on the yield of tuber crops like potato, yam and sweet potato using different crop growth models (Gebremedhin and Berhe 2015 and Mijiyawa *et al.* 2015). There are a few studies that quantified the impact of climate change on cassava cultivation. Liu *et al.* (2008) used the model, GEPIC to study the impact of cassava production in sub-Saharan Africa. Lobell *et al.* (2008) made a similar study and both the above studies observed that cassava will benefit moderately from climate change by 2030. Gleadow *et al.* (2009) observed a reduced growth of cassava due to increased CO₂ concentrations. Schenkler and Lobell (2010) observed that cassava is the least impacted crop compared to many other crops. The study by Jarvis *et al.* (2012) in Africa showed the high resilience of cassava to future climate changes in Africa. Ceballos *et al.* (2011) predicted that future (2020s) climates will maintain cassava production in almost all of the current production areas, with the exception of a few isolated sites in Asia.

The present study is aimed at developing a cassava presence point map based on expert knowledge, to assess what are the projected climatic changes in cassava growing areas of India, to calibrate the EcoCrop model and to model the suitability of current cassava growing areas and to study the impact of future climate (2030 climate) on climate suitability of cassava in India.

¹Research scholar (e mail: sabithasoman836@gmail.com), Division of Crop Production, ²Principal scientist, Division of Crop Production, ³Senior scientist (e mail: sreejyothi_in@yahoo.com), Division of Social Science and Extension.

MATERIALS AND METHODS

For current climate data, we used the WorldClim dataset (Hijmans *et al.* 2005), freely available from the website <http://www.WorldClim.org>. The WorldClim data was prepared by compiling monthly averages of climate as measured at different weather stations from a large number of global, regional, national, and local sources for the period of 1950-2000, then interpolated the data using thin-plate smoothing spline algorithm (Hutchinson 1995) and created global climate surfaces for monthly precipitation and minimum, mean and maximum temperature. The data downloaded for this study was at the resolution of 30 arc-seconds, restricted to India. These datasets were used to analyze the projected climatic changes for cassava growing regions and to assess the impacts on cassava climate suitability.

The future climate projections were also downloaded from the website <http://www.WorldClim.org>. Future data downloaded was the monthly time series of maximum, minimum and mean temperature and total monthly precipitation for SRES-A1B emission scenarios of the 21st century simulations from 22 different coupled global climate models (GCMs) used in the IPCC Fourth Assessment Report (IPCC 2007) for the period 2030s. The data downloaded was at the resolution of 30 arc-seconds restricted to India.

In the present study, according to expert knowledge of scientists working in ICAR-CTCRI and AICRP-TC (All India Coordinated Research Project on Tuber Crops) centers and based on available literature, we identified principal regions where cassava is cultivated currently. We extracted the geographic coordinates (latitude and longitude) of cassava growing regions in India at 2.5 min spatial resolution using the district boundary shapefile of each growing areas. All the spatial analysis was carried out using ArcGIS 10.0 software. We used this point shape file to extract climate data from India grid to study the projected climatic changes in cassava growing areas and to calibrate the EcoCrop model for suitability analysis in DivaGIS.

The original monthly means of mean temperature and total monthly precipitation data from current and future predictions were used to calculate the predicted GCM-specific changes in total annual precipitation (mm) and annual mean temperature ($^{\circ}$ C) for each state of our study area in the areas where the crop is reported to be grown. The individual GCM predicted changes of total annual precipitation and annual mean temperature were plotted as bar graph. The average prediction by 22 GCMs was plotted as box plots using Excel 2007.

The basic mechanistic model (EcoCrop), uses environmental ranges as inputs to determine the main niche of a crop and then produces a suitability index as output. The model was originally developed by Hijmans *et al.* (2001) and named EcoCrop, since it was based on the FAO-EcoCrop database (FAO 2000). In the model, there are two ecological ranges for a given crop, each one defined by a pair of parameters for each variable (i.e. temperature and

rainfall). First, the absolute range, defined by TMIN-C and TMAX-C (minimum and maximum absolute temperatures at which the crop can grow, respectively) for temperature, and by RMIN-C and RMAX-C (minimum and maximum absolute rainfall at which the crop grows, respectively) for precipitation; and second, the optimum range, defined by TOPMIN-C and TOPMAX-C (minimum optimum and maximum optimum temperatures, respectively), and ROPMIN-C and ROPMAX-C (minimum optimum and maximum optimum rainfall, respectively). An additional temperature parameter is used (TKILL) to illustrate the effect of a month's minimum temperature.

The model performs two different calculations separately, one for precipitation and the other for temperatures and then calculates the interaction by multiplying them. We used the EcoCrop model to study the impact of climate change on cassava in India.

The calibration of EcoCrop model for cassava was done following the procedure given by Villegas *et al.* (2013). For each of the data points in the crop dataset, we extracted the corresponding values (from the current climate dataset) for maximum and minimum temperature and total precipitation variables and for each of the 12 months of the year. Then, for each of 12 potential growing seasons (assuming all months are equally likely to be the first month of the growing season), we calculated the average maximum and minimum temperatures and total precipitation. For each point, we then calculated the mean (ME), mode (MO), maximum (MX) and minimum (MN) of all growing seasons for each variable and each point. All the parameter sets were then used to drive the EcoCrop model. For each of the 12 potential growing seasons, we performed 2 runs of the model, one using the minimum temperature parameter set and the other using the maximum temperature parameter set; both of them use the same precipitation parameter set. We then combined the resulting suitability surfaces obtained from the maximum and minimum temperatures parameter sets as given below:

$$SUIT_{TOTALK} = \begin{cases} SUIT_{TMINK} \\ SUIT_{TMAXK} \\ \frac{(SUIT_{TMINK})^2 + (SUIT_{TMAXK})^2}{SUIT_{TMINK} + SUIT_{TMAXK}} \end{cases}$$

$$SUIT_{TMINK} \neq 0; SUIT_{TMAXK} = 0$$

$$SUIT_{TMINK=0}; SUIT_{TMAXK} \neq 0$$

$$SUIT_{TMINK} \neq 0; SUIT_{TMAXK} \neq 0$$

The suitability calculation is done on pixel basis. The $SUIT_{TOTALK}$ is the total suitability of the k^{th} growing season. $SUIT_{TMINK}$ is the suitability of the pixel of the k^{th} growing season, as calculated with the minimum temperature parameter set; $SUIT_{TMAXK}$ is the suitability of the pixel of

the k^{th} growing season, as calculated with the maximum temperature parameter set. In this way, a total of 36 suitability surfaces are finally produced. From these, the one with most accurate distributed prediction is chosen by examining the predictions against the known distribution of the crop (You *et al.* 2007 and 2009, Monfreda *et al.* 2008).

In this study, we used current climate scenario and 22 different future climate scenarios. All the suitability analysis was carried out by using DivaGIS and ArcGIS softwares. We first performed a suitability prediction with the EcoCrop model for current climatic conditions using the derived ecological parameters and then projected the model on to each of the 22 different GCMs (future climate data). For each projection, the change in suitability was calculated on a pixel basis and the following impact matrices were derived for cassava growing regions for each GCM specific predictions.

- (a) The overall suitability change (average % change of all pixels)
- (b) The average suitability change in positively impacted areas (i.e., areas increasing suitability)
- (c) The average suitability change in negatively impacted areas (i.e., areas decreasing suitability)

The results are displayed in tables and the change in suitability predictions by 22 GCMs were averaged and represented as box plot.

RESULTS AND DISCUSSION

Map of cassava presence points in India

We have prepared a point shape file of cassava presence points map in India. We got a total of 10 053 point locations as cassava presence points covering 12 states in India. From these 12 states, 42 districts were identified as current growing areas of cassava in India. Cassava is grown mostly in the southern states of Kerala, Tamil Nadu and Andhra Pradesh.

All the 14 districts in Kerala, 5 districts in Tamil Nadu and 3 districts in Andhra Pradesh were selected for the preparation of cassava presence points map in India.

Projected climatic changes for cassava growing regions

Change in annual mean temperature

Out of the 22 GCMs studied, only two GCMs predicted that the temperatures will remain stable or reduce in some of the current growing areas with annual mean temperature change from -1.3 (Meghalaya) to +0.1°C (Arunachal Pradesh) and from -0.6 (Maharashtra) to +0.28°C (Kerala), respectively. Highest increase in annual mean temperature was predicted for Maharashtra (1.5 to 1.6°C) by three GCMs. An increase of 1.5°C in mean temperature was also predicted for Meghalaya by the GCM 'GISS-MODEL-ER'. The highest and lowest mean temperature changes for Kerala (+1.4 to -1.2°C) and Tamil Nadu (+1.3 to -0.4°C) was predicted by the GCMs, MIROC3.2-HIRES and GISS-AOM, respectively, and the highest and lowest temperature changes for Andhra Pradesh (+1.4 to -0.1°C) was predicted by the GCMs, GISS-MODEL-ER and MRI-CGCM2.3.2A, respectively. The average of the 22 different GCMs showed that by 2030, all the major cassava growing regions in India will have an increase in their annual mean temperature and the predicted increase ranged between 0.9 and 1.2°C (Fig 1). In the states of Kerala, Tamil Nadu and Andhra Pradesh where more than 80% of the India's cassava area is concentrated, the change in annual mean temperature ranged from 0.9 to 1.0°C for Kerala and Tamil Nadu and from 0.9 to 1.1°C for Andhra Pradesh. Out of the 42 districts identified as current growing areas of cassava, 48% districts showed an average increase of 0.9°C in their annual mean temperature, 29% districts showed 1°C increase, 17% districts showed 1.1°C increase and the remaining 7% districts showed 1.2°C increase in their annual mean

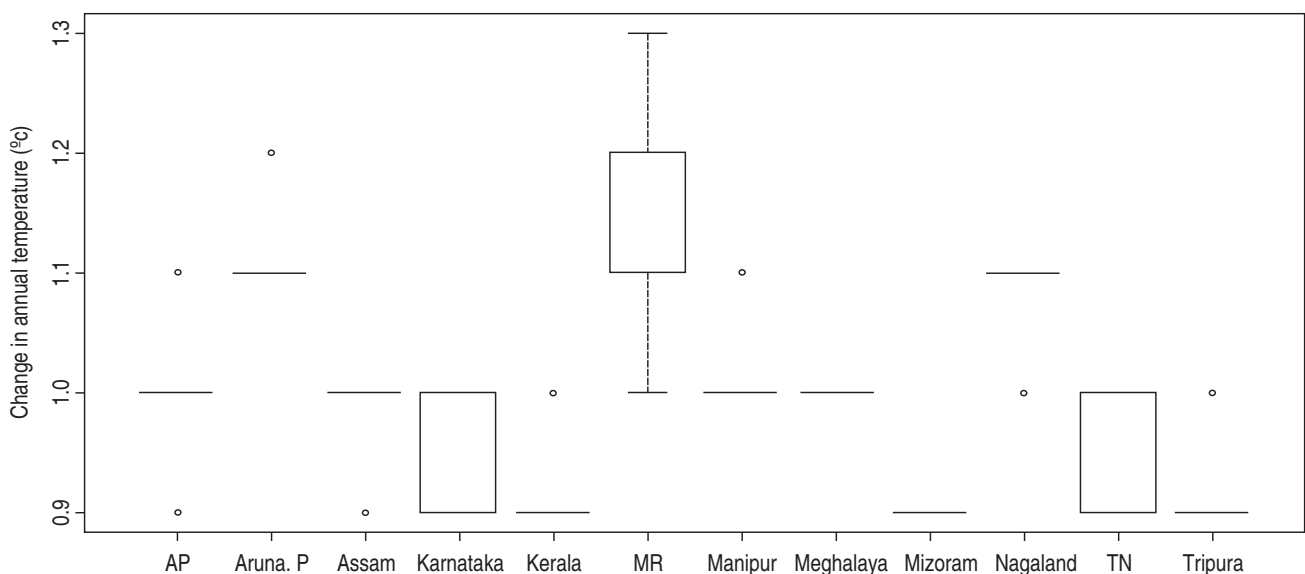


Fig 1 Annual mean temperature change by 2030 for cassava growing states of India

temperature.

Change in total annual precipitation

Out of the 22 GCMs studied, only two GCMs predicted an increase in total annual precipitation in all the cassava growing areas with a range of 57.2 (Tamil Nadu) to 220.5 mm (Andhra Pradesh) and from 40.2 (Karnataka) to 113.5 mm (Andhra Pradesh), respectively, only two GCMs predicted a decrease in annual precipitation by 2030 in all the cassava growing areas with values ranging from -73.3 (Arunachal Pradesh) to -11.2 mm (Maharashtra) and from -155.3 to -16.7 mm (Nagaland), respectively; whereas remaining GCMs showed varying precipitation changes. The highest annual precipitation increase was shown by the GCM 'GISS-MODEL-EH'. The GCM 'MIROC3.2-MEDRES' predicted highest precipitation increase for Kerala (158.9 mm) and Tamil Nadu (180.5 mm) and highest precipitation increase for Andhra Pradesh (220.5 mm) was predicted by the GCM 'CCCMA-CGCM3.1 (T47)'. The mean change of the 22 GCMs showed an increase in the total annual precipitation in all the major growing regions of cassava in India (Fig 2). Predicted changes in annual precipitation for the major cassava growing regions ranged between 6.8 and 112.4 mm/year with the minimum increase in the Dharmapuri district of Tamil Nadu (6.8 mm) and the maximum increase was observed in the South Garo Hills and West Garo Hills of Meghalaya (> 100 mm). In the states of Kerala, Tamil Nadu and Andhra Pradesh, the annual increase in precipitation ranged from 5 to 53 mm (Kerala), 4 to 60 mm (Tamil Nadu) and 6 to 18 mm (Andhra Pradesh), respectively.

The climate change projection in major growing areas of cassava in India showed that the annual mean temperature and total annual precipitation will increase by 2030. The Inter-governmental Panel on Climate Change estimated that the Earth will warm by 1.4 to 5.8°C during the current century (IPCC 2007) and the average mean temperature

will increase by 1 to 2°C during this century (Swaminathan and Kesavan 2012). Continued emissions of green house gases will cause further warming and changes in all components of the climate system. Limiting climate change will require substantial and sustained reduction of green house gas emissions (IPCC 2013). An increase in temperature from 0.7 to 1.3°C in future in the cassava growing regions in Asia was earlier reported by Ceballos *et al.* (2011). An increase in precipitation by 2020 in some Asian countries was also reported by Beebe *et al.* (2011). Mendelsohn *et al.* (1994) predicted positive impacts on agriculture from climate change like increased temperatures and higher carbon dioxide levels because increased concentrations of CO₂ may boost crop productivity, only where moisture is not a constraint. In the present study, the average of the 22 different GCMs studied showed that by 2030, all the major cassava growing regions in India will have an increase in their annual mean temperature ranged between 0.9 and 1.2°C, and an increase in the total annual precipitation ranged between 6.8 and 112.4 mm/year.

Model calibration and parameterization

The selected parameter set to calibrate the EcoCrop model was given in Table 1. The dataset indicates that the crop would die at a temperature ≤ 5°C, and is not suited for temperature below 18°C, the crop grows optimally in the range of 20 to 30°C and will not grow if temperature above 48°C. In the case of precipitation, the crop will harmfully stressed if the total precipitation during the growing season is less than 400 mm (drought stress) or above 3300 mm (excess water) an grows optimally in the range of 600 to 2000 mm precipitation.

Current suitability and model evaluation

The current suitability of the cassava growing regions was studied using the calibrated ecological parameters in EcoCrop. According to the EcoCrop model, highly suitable

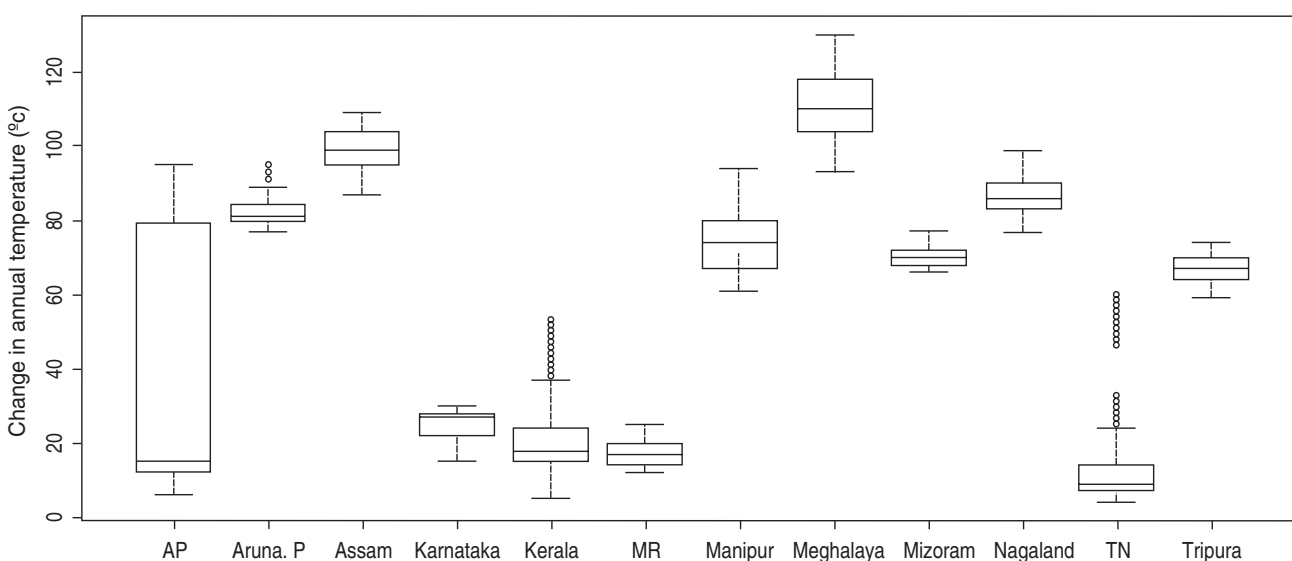


Fig 2 Total annual precipitation change by 2030 for cassava growing states of India

Table 1 Selected parameter set for calibrating ecocrop model

Parameter	Calibrated value
Tkill	5°C
Tmin	18°C
Topmin	20°C
Topmax	30°C
Tmax	48°C
Rmin	400 mm
Ropmin	600 mm
Ropmax	2000 mm
Rmax	3300

areas for growing cassava (> 80%) were predicted to be located in the states of Kerala, Tamil Nadu, Andhra Pradesh, Karnataka, Maharashtra and in some north eastern states, matching the known distribution of the crop. The current suitability prediction done by the model showed that the suitability of all districts in Kerala ranged from 80 to 100%. About 40% of districts in Tamil Nadu showed 80 to 100 % suitability, whereas in Salem, Namakkal and Dharmapuri districts of Tamil Nadu, the current suitability prediction ranged from 50 to 100%. The suitability of Andhra Pradesh ranged from 20 to 100% with 80 to 100% suitability in the East Godavari and West Godavari districts of Andhra Pradesh.

Future predictions of suitability and impacts on cassava

The future predictions on cassava climatic suitability showed that, on an average, cassava production in India is favored by climate change or there are not much decreases in cassava climatic suitability by 2030. The future suitability predictions in the major growing areas were almost similar as in the current suitability predictions. All districts in Kerala, Salem, Namakkal and Dharmapuri districts in Tamil Nadu, East Godavari and West Godavari districts in Andhra Pradesh showed almost similar suitability prediction by the model in the current and future climatic conditions. All the north eastern states showed similar suitability percentage by 2030 as in the current condition. The individual GCM predicted changes in suitability is presented in Table 2. The overall suitability change in the cassava growing regions ranged between -10 (IAP-FGOALS1.0-G) and 6.68% (NCAR-CCSM3.0) with suitability change in positively and negatively impacted areas ranged from 3.63 to 23.70% and from -18.59 to -2.66%, respectively. Out of the 22 GCMs studied, 50% GCMs predicted a suitability change of -1 to -3 % in Kerala and the remaining predicted positive change in suitability. About 41% GCMs predicted negative suitability change in Tamil Nadu (-19 to -1%) and the remaining predicted positive change. About 55% GCMs predicted a suitability change of -19 to -1% and the remaining GCMs predicted a positive suitability change in Andhra Pradesh.

Suitability changes in the cassava growing states ranged between -2 (Andhra Pradesh) and 15% (Meghalaya). No severe impacts were observed in the cassava growing regions by 2030. The predicted changes were negative for Andhra

Pradesh (-2.2%), Asom (-1.2), and Karnataka (-1.2) but the values are negligible. In the major production areas, about 66% states showed a little an increase in climate suitability for cassava. The suitability changes in Kerala, Tamil Nadu and Andhra Pradesh were in the range of -7 to 49%, -4 to 46% and -6 to 5%, respectively. In the case of other growing areas, the suitability change was in the range of -10 to 38% for Arunachal Pradesh, -10 to 27% for Asom, -6 to 47% for Karnataka, -5 to 41% for Maharashtra, -10 to 38% for Manipur, 0 to 32% for Meghalaya, -8 to 23% for Mizoram, -9 to 38 % for Nagaland and -5 to 18% for Tripura.

The EcoCrop model was used by different authors like Parthasarthy *et al.* (2007) for turmeric site suitability prediction in India, Villegas *et al.* (2013) to assess the impact of climate change on sorghum in Africa and South Asia and Jarvis *et al.* (2012) for suitability study of cassava in Africa. In the present study, we have calibrated and validated the EcoCrop model for cassava in India. The model was earlier calibrated for cassava (Ceballos *et al.* 2011) and other crops like beans (Beebe *et al.* 2011), sorghum (Villegas *et al.* 2013), etc. Using the calibrated data we have made predictions for the current and future climatic conditions using the EcoCrop model and the resulting suitability maps showed that the current cassava growing areas have almost similar suitability in the future climatic conditions also. The major growing areas like Kerala, Tamil Nadu and Andhra Pradesh and the north eastern states

Table 2 Regional changes in cassava suitability for individual GCMs

GCM	OSC*	SCPIA*	SCNIA*
CCCMA-CGCM3.1 (T47)	5.17	15.19	-5.67
CCMA-CGCM3.1 (T63)	3.05	14.69	-6.63
CNRM-CM3	2.95	11.25	-3.24
CSIRO-MK3.0	5.01	12.62	-2.66
CSIRO-MK3.5	-0.33	9.95	-4.36
GFDL-CM2.0	-2.01	15.92	-6.97
GFDL-CM2.1	-1.06	16.55	-7.53
GISS-AOM	-0.14	20.85	-4.55
GISS-MODEL-EH	-6.25	13.97	-17.57
GISS-MODEL-ER	-0.02	8.05	-7.26
IAP-FGOALS1.0-G	-10.01	4.97	-18.59
INGV-ECHAM4	-2.31	23.15	-8.25
INM-CM3.0	3.47	12.65	-3.26
IPSL-CM4	-1.34	8.99	-3.89
MIROC3.2-HIRES	-1.83	20.10	-10.39
MIROC3.2-MEDRES	6.05	19.88	-6.70
MPI-ECHAM5	-0.89	3.63	-3.67
MRI-CGCM2.3.2A	3.76	23.70	-8.78
NCAR-CCSM3.0	6.68	17.03	-3.91
NCAR-PCM1	1.35	23.44	-12.17
UKMO-HADCM3	3.70	11.13	-3.04
UKMO-HADGEM1	-4.74	10.47	-8.81

OSC*- overall suitability change, SCPIA*- suitability change in positively impacted area, SCNIA*- suitability change in negatively impacted area.

showed similar suitability prediction by the model in the current and future climatic conditions.

The overall suitability change predicted by individual GCMs in the cassava growing regions ranged between -10 and 6.68%. The changes in suitability as an average of 22 GCMs for the major cassava growing states were observed to be from -2.2 to 15.1%. Jarvis *et al.* (2012) reported a positive impact of cassava in Africa to 2030 climate with a suitability change of -3.7 to 17.5%. The results of our study showed that the 2030 climate will maintain cassava production in almost all of the current cassava growing states in India. There are different studies which showed a substantial increase in area of cassava suitability in different parts of the world (Ceballos *et al.* (2011); Jarvis *et al.* (2012) and Kamukondiwa (1996)). Different authors reported the beneficial characteristics and resilience of cassava (Liu *et al.* (2008); Lobell *et al.* (2008) and Schlenker and Lobell (2010)) in the context of climate change. Our results will also agree with these findings.

Through modeling and quantitative data analysis, we have evaluated the impacts of climate change on cassava production in India. It is also difficult to quantitatively compare the results of the study with other studies mainly because there are (1) different emission scenarios (2) a different set of GCMs (3) a different time period (future climate) or (4) a combination of the above facts (Villegas *et al.* 2013). The suitability model only takes into account two major facts: temperatures and precipitation. However, for cassava some other factors like increased CO₂ concentration, soil conditions, and changes in pest and disease dynamics must also be taken into account for production forecasting model in order to refine predictions (Ceballos *et al.* 2011). Using the EcoCrop model, the predictions showed that in future, cassava is performing well in the areas where it grows currently in India.

REFERENCES

- Abdul Haris A V, Biswas S, Chhabra V, Elanchezhian R and Bhatt B P. 2013. Impact of climate change on wheat and winter maize over a sub-humid climatic environment. *Current Science* **104** (2): 206–14.
- Aggarwal P K. 2007. Climate change: Implications for Indian agriculture. *Jalvignyan Sameeksha* **22**: 37–46.
- Beebe S, Ramirez J, Jarvis A, Rao I M, Mosquera G, Bueno J M and Blair M W. 2011. Genetic improvement of common beans and the challenges of climate change. *Crop adaptation to climate change*, Shyam S Y, Robert J R, Jerry L H, Hermann L C, Anthony E H (Eds). John Wiley and Sons.
- Ceballos H, Ramirez J, Bellotti A C, Jarvis A and Alvarez E. 2011. Adaptation of cassava to changing climates. *Crop adaptation to climate change*, Shyam S Y, Robert J R, Jerry L H, Hermann L C and Anthony E H (Eds). John Wiley and Sons.
- Challinor A J, Osborne T, Shaffrey L, Weller H, Morse A, Wheeler T and Vidale P L. 2009. Methods and resources for climate impacts research. *Bulletin of American Meteorological Society* **90**: 836–48.
- Chao, C, Guang-sheng Z and Li Z. 2014. Impacts of climate change on rice yield in China from 1961 to 2010 based on Provincial data. *Journal of Integrative Agriculture* **13**(7): 1 555–64.
- Cock J H. 1985. *Cassava: New Potential for a Neglected Crop*. Boulder, Col. Westview.
- Edison S, Anantharaman M and Srinivas T. 2006. *Status of cassava in India: An overall view*. Technical Bulletin Series: 46, Central Tuber Crops Research Institute.
- FAO. 2000. *The EcoCrop database*. Food and Agriculture Organization of the United Nations, Rome, Italy.
- Gebremedhin Y and Berhe A A. 2015. Impact of climate change on potato yield (*Solanum tuberosum* L.) at Mekelle Areas, in Northern Ethiopia. *World Journal of Agricultural Sciences* **11**(2): 62–9.
- Gleadon R M, Evans J R, McCaffery S and Cavagnaro T R. 2009. Growth and nutritive value of cassava (*Manihot esculenta* Cranz.) are reduced when grown in elevated CO₂. *Plant Biology* **11**: 76–82.
- Hijmans R J, Cameron S E, Parra J L, Jones P G and Jarvis A. 2005. Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology* **25**: 1 965–78.
- Hijmans R J, Guarino L, Cruz and Rojas E. 2001. Computer tools for spatial analysis of plant genetic resources data: 1. DIVA-GIS. *Plant Genetic Resource Newsletter* **127**: 15–9.
- Hutchinson M F. 1995. Interpolating mean rainfall using thin plate smoothing splines. *International Journal of Geographical Information System* **9**: 385–403.
- IPCC. 2007. *IPCC Fourth Assessment Report: Climate Change 2007 (AR4)*. IPCC, Geneva, Switzerland.
- IPCC. 2013. *Climate Change 2013 The physical science basis*. IPCC, Geneva, Switzerland.
- Jarvis A, Villegas J R, Herrera Campo B V and Navarro-Racines C. 2012. Is cassava the answer to African climate change adaptation?. *Tropical Plant Biology* **5**: 9–29.
- Kamukondiwa W. 1996. Alternative food crops to adapt to potential climatic change in southern Africa. *African Climate Research* **06**: 153–5.
- Liu J, Fritz S, van Wesenbeeck C F A, Fuchs M, You L, Obersteiner M and Yang H. 2008. A spatially explicit assessment of current and future hotspots of hunger in Sub-Saharan Africa in the context of global change. *Global Planet Change* **64**: 222–35.
- Lobell D B, Burke M B, Tebaldi C, Mastrandrea M D, Falcon W P and Naylor R L. 2008. Prioritizing climate change adaptation needs for food security in 2030. *Science* **319**: 607–10.
- Mendelsohn R O, Nordhaus W D and Shaw D. 1994. The impact of climate change on agriculture: A Ricardian Analysis. *American Economic Review* **84**(4): 753–71.
- Mijiyawa Y, Akpenpuun T D and Amao B R. 2015. Climate change effect on tuber crops yield in the tropics. *International Journal of Engineering & Technology Innovations* **2**(2): 10–3.
- Monfreda C, Ramankutty N and Foley J A. 2008. Farming the planet. 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles* **22**(1): GB1022.
- Nasser N, Vizzotto C S, Schwartz C R and Pires O R. 2007. Cassava diversity in Brazil: The case of carotenoid-rich landraces. *Genetics and Molecular Research* **6**(1): 116–21.
- Parthasarthy U, Johny A K, Jayarajan K and Parthasarathy V A. 2007. Site suitability for turmeric production in India A GIS interpretation. *Natural Product Radiance* **6**(2): 142–7.
- Schlenker W and Lobell D B. 2010. Robust negative impacts of climate change on African agriculture. *Environmental Research Letter* **5**: 014010.

- Senapati M R, Behera B and Mishra S R. 2013. Impact of Climate Change on Indian Agriculture & Its Mitigating Priorities. *American Journal of Environmental Protection* **1**(4): 109–11.
- Swaminathan M S and Kesavan P C. 2012. Agricultural research in an Era of climate change. *Agricultural Research* **1**(1): 3–11.
- Villegas J R, Jarvis A and Laderach P. 2013. Empirical approaches for assessing impacts of climate change on agriculture: The EcoCrop model and a case study with grain sorghum. *Agricultural and Forest Meteorology* **170**: 67–78.
- You L, Wood S and Wood-Sichra U. 2009. Generating plausible crop distribution maps for Sub-Saharan Africa using a spatially disaggregated data fusion and optimization approach. *Agricultural Systems* **99**: 126–40.
- You L, Wood S, Wood-Sichra U and Chamberlin J. 2007. Generating plausible crop distribution maps for sub-Saharan Africa using a spatial allocation model. *Information Development* **23**(2-3): 151–9.