Impact of climate change on crop productivity in Western Ghats, coastal and northeastern regions of India

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Assessment on impact of climate change on major crops in ecologically sensitive areas, viz. the Western Ghats (WG), coastal districts and northeastern (NE) states of India, using InfoCrop simulation model, projected varying impacts depending on location, climate, projected climate scenario, type of crop and its management. Irrigated rice and potato in the NE region, rice in the eastern coastal region and coconut in the WG are likely to gain. Irrigated maize, wheat and mustard in the NE and coastal regions, and rice, sorghum and maize in the WG may lose. Adaptation strategies such as change in variety and altered agronomy can, however, offset the impacts of climate change.

Keywords: Agriculture, climate change, crop productivity, impact assessment, simulation model.

INDIAN agriculture is facing challenges due to several factors such as increased competition for land, water and labour from non-agricultural sectors and increasing climatic variability. The latter associated with global warming will result in considerable seasonal/annual fluctuations in food production. All agricultural commodities even today are sensitive to such variability. Droughts, floods, tropical cyclones, heavy precipitation events, hot extremes and heat waves are known to negatively impact agricultural production, and farmers' livelihood. It has been projected by the recent report of the IPCC and a few other global studies that unless we adapt, there is a probability of 10–40% loss in crop production in India by 2080–2100 due to global warming[1–4], despite beneficial aspects of increased CO_2. A recent meta-analysis of CO_2 enrichment experiments in fields has shown that in the field environment, 550 ppm CO_2 leads to a benefit of 8–10% in yield in wheat and rice, up to 15% in soybean, and almost negligible in maize and sorghum[5]; but increase in temperature may alter these results.

Earlier studies conducted in India also generally confirm the trend of agricultural decline with climate change[6–12]. Projections indicate the possibility of loss of 4–5 million tonnes in wheat production with every rise of 1°C temperature throughout the growing period with current land use[12]. In March 2004, temperatures were higher in the Indo-Gangetic plains by 3–6°C, which is equivalent to almost 1°C per day over the whole crop season. As a result, wheat crop matured earlier by 10–20 days and wheat production dropped by more than 4 million tonnes in the country[13]. Losses were also significant in other crops, such as mustard, peas, tomatoes, onion, garlic and other vegetable and fruit crops[13]. Similarly, the drought of 2002 led to reduced area coverage of more than 15 m ha of the rainy-season crops and resulted in a loss of more than 10% in food production[14]. The projected increase in these events could result in greater instability in food production and threaten livelihood security of farmers. Recent simulation analysis projects adverse impacts on maize yields in kharif due to rise in atmospheric temperature; but increased rainfall can partly offset those loses. Spatio-temporal variations in projected changes in temperature and rainfall are likely to lead to differential impacts in the different regions[15]. Analysis on sorghum also indicated that the yield loss due to rise in temperature is likely to be offset by projected increase in rainfall. However, complete amelioration of yield loss beyond 2°C rise may not be attained even after the doubling of rainfall[16].

While the above review indicates gross effects of climate change on crops in India, there are several special ecosystems that are ecologically and economically important, but assessment of impacts on agriculture in these regions has not received adequate attention. These regions include the Western Ghats, coastal areas and the northeastern region. Agriculture in these areas is multi-dimensional ranging from rice-based agriculture, horticultural crops, plantations, fisheries and dairy. The three regions cover almost 200 districts, which is one-third of the total number of districts in India.

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Table 1. Area, production and productivity of major crops in the districts covering the Western Ghats, coastal and northeastern regions

Crop/sector	Area ('000 ha)	Production ('000 t)	Productivity (kg/ha)
Western Ghats			
Rice	2685	6530	2387
Sorghum	2944	1751	863
Maize	784	1778	2046
Groundnut	910	1008	1207
Coconut	1409	8369 ('000 nuts)	5353 (nuts)
Arecanut	232	285	1196
Cardamom	66	10	74
Tea	108	210	1325
Coffee	259	225	752
Cashew	176	76	384
Rubber	244	302	962
Black pepper	229	91	952
Tapioca	164	4566	25243
Coastal districts			
Rice	6248	15520	2300
Maize	2056	4824	1936
Groundnut	1777	2153	1559
Urad	692	376	477
Red gram	579	248	433
Cotton (lint)	796	1528	2104
Coconut	1003	7077	8243
Cashew	796	1528	2104
Marine fish		29.2 (lakh t)	
Shrimps		144.4	
Scampi			
Northeastern region			
Tea	284	443	1211
Arecanut	82	75	947
Rice	3259	5195	1636
Wheat	78	98	1433
Maize	119	170	1210
Rapeseed and mustard	278	151	964
Potato	114.7	1042	8120

Agriculture in the Western Ghats

The Western Ghats, one of the 24 global hot spots of biodiversity, comprises of 63 districts in Kerala, Tamil Nadu, Karnataka, Maharashtra and Gujarat in peninsular India. Agriculture in this relatively high-elevation area (average elevation is 1200 m) is characterized, in general, by four typologies: (i) large tea, coffee and rubber estates; (ii) other plantations and spices which are generally grown as inter crops along with annual crops; (iii) annual crops-based farming consisting of mainly paddy, vegetables, pulses, tuber crops and millets, and (iv) homestead farming. Even though the area under annual crops is less in the Western Ghats area, agricultural diversity is substantial (Table 1). About seven cereal crops, nine oilseed crops, five types of pulse crops, six types of plantation species, more than 20 types of spices, and a number of species of medicinal and aromatic plants, vegetables and horticultural crops are being grown. Area under plantation crops such as tea, coffee and rubber is generally confined to high elevations and slopes, whereas area under coconut, arecanut, cashew and spices dominates the lower slopes and valleys. Annual crops such as rice, sorghum, pulses and vegetables are mainly grown in lower elevations.

Agriculture in coastal districts

India has a long coast of about 9000 km and agriculture in the coastal districts has rich agro-biodiversity. Many of the costal districts are fed by the river streams, river deltas and back-water streams. In these areas, bulk of the agricultural output is from not only crop production, but also from fisheries and aquaculture supporting the livelihood of millions. Rice is the major staple crop in the coastal region. In addition, horticultural crops and plantations, especially coconut predominate coastal agriculture.

In this analysis, all districts having the sea coast as a part of their boundary are considered as the coastal areas.

Agriculture in the northeastern region

Northeastern India, comprising Arunachal Pradesh, Assam, Manipur, Meghalaya, Mizoram, Nagaland, Sikkim and Tripura has a total cropped area of 5.3 m ha and a population of around 39 million. In the NE states, there are broadly two distinct types of agricultural practices, viz. (i) settled farming practised in the plains, valleys, foothills and terraced slopes, and (ii) shifting cultivation (Jhum) practised on the hill slopes. The region is rich in biodiversity and major areas are under sustenance agriculture. Rice is the major annual crop in this region, while tea, jute, cotton, potato, sugarcane and oilseeds are the major cash and annual crops. Horticulture is also diverse in this region with major crops being as orange, banana, pineapple, arecanut, coconut, guava, mango and jackfruit[17].

Keeping in view the ecological and economic importance of these areas, diversity of agriculture and its importance for sustainable livelihood of the local population, the present study was conducted to assess the impact of climate change scenario for the 2020–2050 period (2030 scenario) on major crops in these regions.

Materials and methods

Simulation analysis using InfoCrop

The impact of climate change was assessed for major cereals (rice, wheat, maize and sorghum), oilseed (mustard), a horticultural crop (potato) and a plantation crop (coconut) using a simulation model called InfoCrop. This is a generic crop growth model that can simulate the effects of weather, soil, agronomic management (including planting, nitrogen, residue and irrigation) and major pests on crop growth and yield[18]. The model considers different crop development and growth processes influencing the simulation of yield. The total crop growth period in the model is divided into three phases, viz. sowing to seedling emergence, seedling emergence to anthesis and storage organ-filling phases. The model requires various varietal coefficients, viz. thermal time for phenological stages, potential grain weight, specific leaf area, maximum relative growth rate, maximum radiation use efficiency, etc. Crop management inputs into the model include time of sowing, application schedule and amount of fertilizer and irrigation. Soil input data include soil pH, soil texture, thickness, bulk density, saturated hydraulic conductivity, soil organic carbon, slope, soil water-holding capacity and permanent wilting point. Location-wise daily weather data (solar radiation, maximum and minimum temperatures, rainfall, wind speed and vapour pressure) are also required to simulate crop performance.

In InfoCrop, change in temperature, CO_2 and rainfall are simulated in the following ways:

1. The total development of a crop is calculated by integrating the temperature-driven development rates of the phases from sowing to seedling emergence, seedling emergence to anthesis and storage organ-filling phases. The rate of development is linearly related to the daily mean temperature above the base temperature up to the optimum temperature. Above this, the rate decreases. Therefore, depending upon the threshold temperature of a region, increase in temperature generally accelerates phenology and hence crop duration is reduced.
2. Dry matter production is a function of radiation use efficiency (RUE), photosynthetically active radiation, total leaf area index (LAI), and a crop/cultivar-specific light interception coefficient. RUE is further governed by a crop-specific response of photosynthesis to temperature, water, nitrogen availability and other biotic factors. Carbon dioxide concentration has no direct influence on photosynthesis of a C4 crop. But under water-stressed conditions, increase in CO_2 indirectly increases photosynthesis and yield by reducing water use and delaying drought stress via reduction in stomatal conductance and transpiration rate[19].
3. The net dry matter available each day for crop growth is partitioned as a crop-specific function of development stage, which as mentioned earlier is influenced by temperature.
4. In the initial stages of crop growth, leaf area formation is controlled by temperature. Senescence of leaves is also dependent on temperature.
5. Temperature influences potential evapotranspiration. Water stress is determined as the ratio of actual water uptake and potential transpiration. It accelerates phenological development, decreases gross photosynthesis, alters the allocation pattern of assimilates to different organs and accelerates the rate of senescence.
6. Adverse temperatures during meiosis stage could significantly increase sterility. In InfoCrop, a part of the storage organ becomes sterile if either maximum or minimum temperatures of the day deviate from their respective threshold values during a short period between anthesis and a few days afterwards. This reduces the number of storage organs available subsequently for accumulating weight. The storage organ starts filling up shortly after anthesis with a rate depending upon temperature, potential filling rate and the level of dry matter available for its growth.
7. Influence of rainfall is operated in the model through soil water balance.

The InfoCrop model is well calibrated and validated for wheat and rice[20], maize[15], sorghum[16], mustard[21], potato[22] and coconut[23] crops for the Indian region. These calibrated and validated models were used for simulating the yields during the baseline period (1969–1990) and also for assessment of impacts.

Processing of input data

The following inputs were used in the model:

1. Weather data: IMD 1° × 1° gridded data for the baseline period (1969–1990).
2. Soil data rescaled to grid values from NBSSLUP and ISRIC soil database.
3. Crop management: normal crop practices as followed by the farmers.
4. Genetic coefficients of varieties best suitable for different regions.
5. Climate change scenarios of PRECIS A1b for the 2030 (2020–2050) period.

Weather: The IMD 1° × 1° daily gridded data on rainfall, and minimum and maximum temperatures were processed using the MS-Excel macro and arranged grid-wise. These data were converted to InfoCrop weather file format using a custom-made software. Thus files for 22 years each (1969–1990) for all corresponding grids were made. In simulations, solar radiation was calculated by the model based on Hargreaves method, which is reported to be best suited for Indian conditions[24]. The potential evapotranspiration was calculated by the model using the Priestly and Taylor method.

Soil data: The data on soil parameters such as texture, water-holding characteristics, bulk density, soil pH and depth of three soil layers were obtained from NBSSLUP, Nagpur and also from the database of ISRIC. The data were input grid-wise into the model. Pedo-transfer functions were used to derive the hydraulic characteristic coefficients.

Varietal coefficients: Simulations were carried out assuming that the farmers have successfully optimized their resources in terms of variety and sowing time. Respective coefficients for all crops were taken for the dominant Indian varieties from the previous published studies. These were calibrated for each grid by simulating the performance of short, medium and long-duration varieties grown during timely, late and very late sown periods respectively. The best combination was taken for the baseline and impact assessment.

Management: In order to mimic the situation in the farmers' field conditions, the crop was provided with the respective recommended doses of fertilizers for irrigated and rainfed crops. Irrigation was provided at the desired stages in the irrigated crops. It was assumed that the crops were maintained free of pest and disease infestation in the field.

Estimating impact of climate change

Estimating baseline production: Simulations were done with the InfoCrop model for each crop using the respective crop coefficients and management for each of the 22 years. The mean of 22 years yield was taken as the baseline yield. To obtain the district yields, grid yields were interpolated using GIS. The weighted area of each grid in a district was multiplied with the grid yield to get a dimensionless value. These values from all grid portions falling in a district were summed to get the 'district value'. These values were calibrated to district production by multiplying with the ratio between district production and the 'district value'. The production figures were calibrated to mean production values of 2000–2005 for each district and henceforth will be referred to as 'baseline yields'.

Simulating production in future scenarios: The impact of climate change on yield of crops was studied using A1b 2030 scenario derived from the PRECIS regional climate model (RCM), provided by the Indian Institute of Tropical Meteorology (IITM), Pune. PRECIS is a RCM with HadCM3 as its global climate model (GCM). The outputs of the climate model on temperature (minimum and maximum) and rainfall for the A1b-2030 scenario were processed to derive the difference fields from the baseline values for the respective scenario, which is referred to as delta method. These difference fields were coupled to the baseline weather data to get the scenario climate data. The major advantage of this method is overcoming the biases of the climate model for baseline weather. Apart from this, the frequency of occurrence of climatic extreme events such as higher/low rainfall events and high-temperature events is inherently accounted for. However, the assumption of distribution of rainfall remaining similar in future scenarios as that of the baseline period is a major limitation of this method. The projected CO_2 levels according to the Bern CC model for scenario was also included for the simulations. All other simulation conditions were maintained as explained earlier. Based on the simulated yields in changed scenarios, production was calculated as in case of baseline production assuming that the area under each crop in each district would remain the same in future as well.

To express the impacts on productivity, the net change in productivity in the climate change scenario was calculated and expressed as the percentage change from the baseline mean productivity. Grid-wise values were further processed in GIS platform for mapping the impacts in the study regions.

Results and discussion

Projected impacts of climate change on crops in the Western Ghats in the 2030 scenario

The simulation analysis indicates that the productivity of kharif crops such as irrigated rice in the Western Ghats region is likely to change by +5% to –11% in the PRECIS A1b 2030 scenario depending upon the location. Majority of the region is projected to lose the yields by about 4% (Figure 1). In case of rainfed rice, the projected change in yield is in the range –35% to 35%, with a large portion of the region likely to lose rice yields up to 10%. Results thus indicate that rice is able to benefit due to CO_2 fertilization in some locations. Since irrigated rice, in general, is supplied with better amount of fertilizers than the rainfed rice, it has better opportunity to benefit from CO_2 fertilization effects for production and accumulation of dry matter and hence grain yield. Irrigated rice in parts of southwestern Karnataka and the northern-most districts of Kerala is likely to gain. In these areas, current seasonal minimum and maximum temperatures are relatively lower (20–22°C $T_{\min}$; 27–28°C $T_{\max}$). The projected increase in maximum temperature is also relatively less in these areas (1–1.5°C) as also increase in minimum temperature, which is projected to be about 1.3°C.

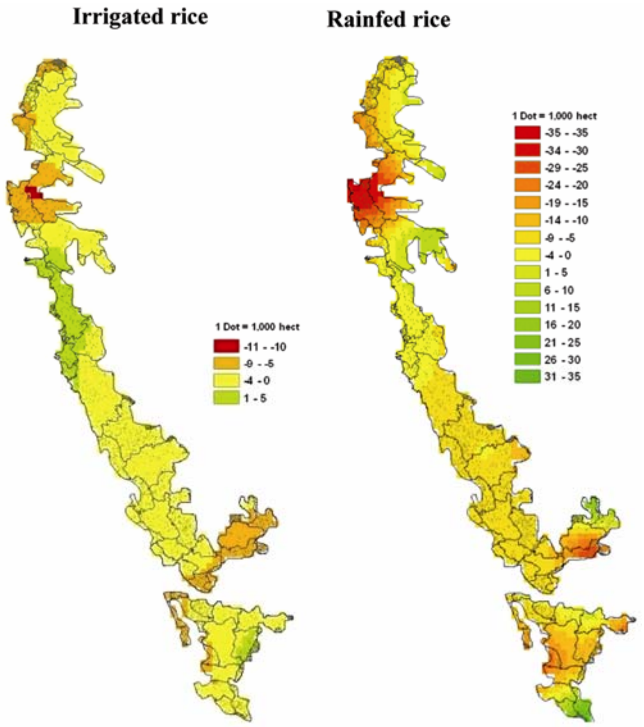

Figure 1. Projected change in yield of rainfed and irrigated rice in the Western Ghats due to climate change in the PRECIS A1b 2030 scenario. The values are percentage of deviation from current yields. Each dot represents the crop area and its distribution.

In most of the Western Ghats region, the monsoon rainfall is likely to increase up to 15%. However, in the eastern part of the Western Ghats (falling in Tamil Nadu), in addition to greater rise in maximum (~ 2.2°C) and minimum (~ 1.7°C) temperatures, rainfall is projected to be reduced by about 20%. These changes in temperature and rainfall cause direct impacts on the production of kharif crops as indicated in this study. Variable response in rainfed rice can be attributed to the influence of the major limiting factor at a given location, viz. rainfall, temperature and nutrient supply. Increased rainfall can be a surrogate for reduced sunshine duration due to cloudiness, causing limitation to photosynthetic rates resulting into reduced accumulation of dry matter, particularly in areas with high rainfall. Since the Western Ghats receives high rainfall, it can be inferred that heavy cloud cover causing low radiation is one of the limiting factors for higher productivity in this region; any further increase in rainfall (thus more cloudiness) will result in reduced yields during the kharif season. Farmers in the Western Ghats region falling in the northwest part of Tamil Nadu, northern part of Kerala and in some parts of Karnataka can reduce the impacts of climate change and reap higher harvests by adopting crop management strategies such as soil moisture conservation, provision for proper drainage, increased efficiency of water and nutrient supply and utilization, and by growing cultivars tolerant to adverse climate.

Climate change is likely to reduce yields of maize and sorghum by up to 50% depending upon the region (Figure 2). These crops have C4 photosynthetic system and have relatively lesser advantage than C3 crops at higher CO_2 concentrations[25]. Increase in rainfall in already high-rainfall zones is detrimental to crop production, as mentioned earlier. Further, increased temperature causes reduction in the crop duration due to increased growth rates. Reduced crop duration means less opportunity for the crop canopy to accumulate the photosynthates and thus dry matter. These conditions can cause the reduction in grain yield as indicated in this analysis. Further, any coincidence of high rainfall with the pollination period will affect the production to spikelet sterility, especially in cross-pollinated crops such as maize and sorghum.

In the Western Ghats region, coconut is confined to low altitudes with rare presence in mid and high altitudes. In contrast to the annual kharif crops, the yield of coconut, a perennial plantation crop, is projected to increase by up to 30% in majority of the region due to climate change (Figure 2). Increase in coconut yield may be mainly attributed to projected increase in rainfall (~ 10%) and relatively less increase in temperatures, apart from CO_2 fertilization benefits. Coconut has a unique phenology, wherein it produces one leaf and one inflorescence at almost monthly interval. Increased temperature can

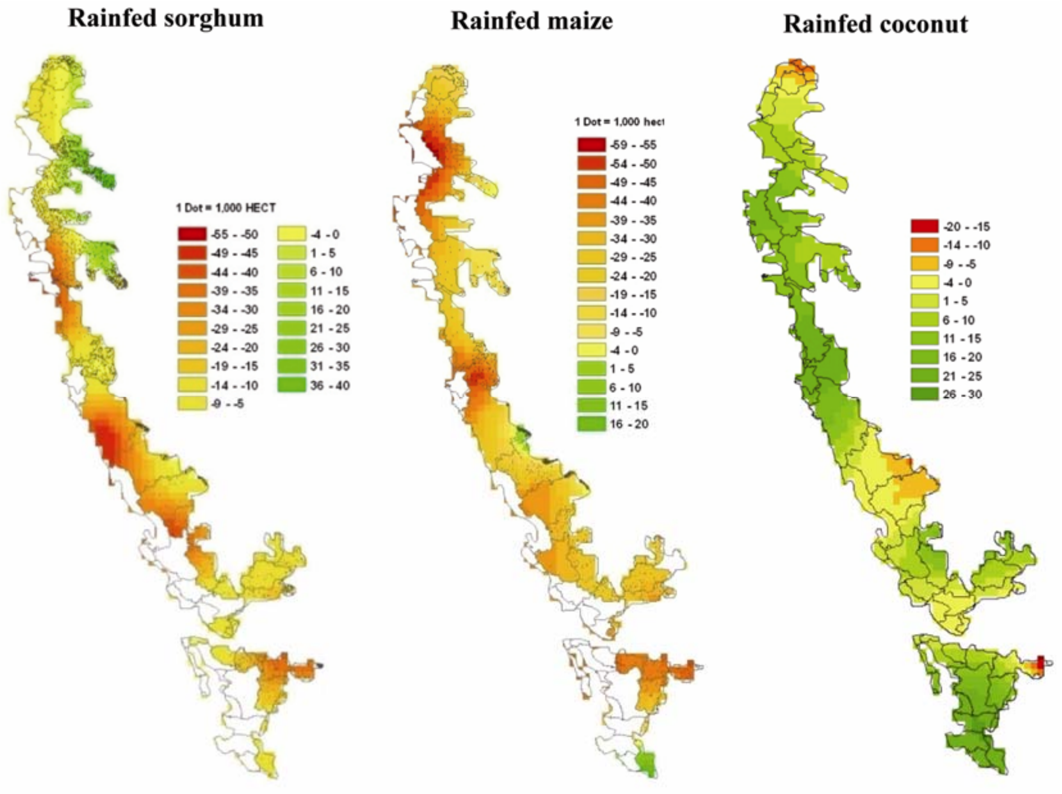

Figure 2. Projected changes in yield of rainfed sorghum, maize and coconut in the Western Ghats due to climate change in the PRECIS A1b 2030 scenario. The values are percentage of deviation from current yields. Each dot represents the crop area and its distribution.

increase the leaf and inflorescence production rates, putting up better canopy for higher photosynthesis during clear days from October to May. This can compensate for reduced sunlight during the monsoon season and even improve dry matter production, resulting into higher nut yield in future climate scenario. Further, rainfall is projected to increase up to 15% during November–March. This condition favours rainfed coconut plantations in the region (most of the plantations are rainfed) due to prolonged moisture availability for increased accumulation of photosynthates. Added to these, temperatures are projected to increase up to 2°C during November–March in these areas causing the ambient temperatures to shift towards the optimum for growth of coconut during this period. Annual temperature increase is projected to be around 2°C for both maximum and minimum temperatures. Since current temperatures are relatively low in these areas, increase in temperature by 2°C can prove beneficial to the metabolic activities of coconut palm, which has temperature optima of about 28°C. However, some areas of the Western Ghats falling under southwest Karnataka, parts of Tamil Nadu and parts of Maharashtra are likely lose yield up to 24%. Current temperatures in these areas are already high and rainfall, which is currently less, is projected to reduce further, affecting the growth and yield of coconut.

Probable impacts of climate change on crops in coastal districts in 2030 scenario

Coastal districts have, in general, warm and humid climate. The east coast face threats from frequent cyclones, heavy winds and floods, whereas the west coast faces heavy rainfall events and in some parts and sea-water intrusion. All these cause severe damage to agricultural production. Apart from these, climate change in terms of increased temperature, change in rainfall and elevated CO_2 is also likely to influence the performance of agriculture in the region. Climate change in the 2030 scenario is projected to affect the yields of irrigated rice up to 10% in majority of the coastal districts (Figure 3). However, in some coastal districts of Maharashtra, northern Andhra Pradesh and Orissa irrigated rice yields are projected to marginally increase ($< 5\%$). On the other hand, rainfed rice yields are projected to increase up to 15% in many of districts in the east coast, but reduce by up to 20% in the west coast. Impacts of climate change on irrigated maize in the coastal districts are projected to be much higher with likely yield loss between 15% and 50%, whereas rainfed maize is projected to lose up to 35%. But, in some districts of coastal Andhra Pradesh, rainfed maize yield is likely to increase by 10%. Projected increase in seasonal maximum temperature during kharif in these areas is less than 1°C in the 2030 scenario.

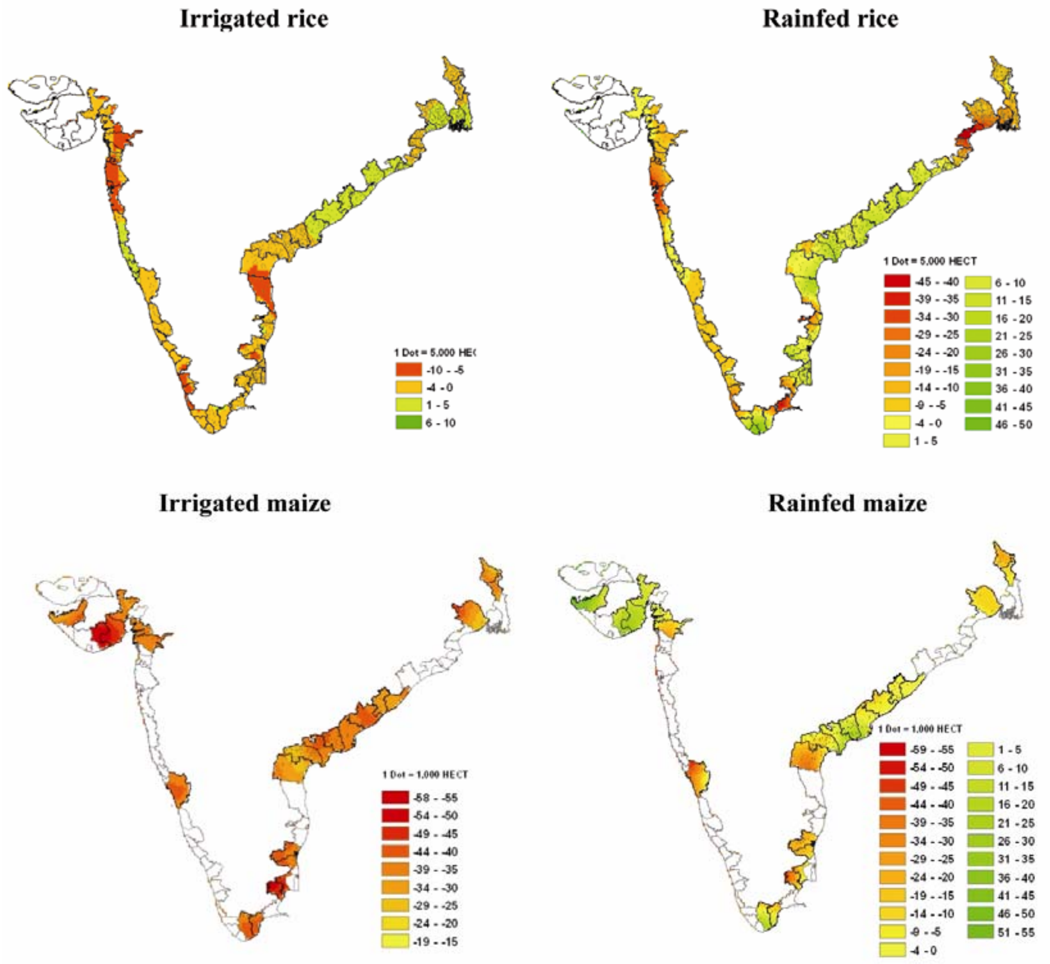

Figure 3. Impact of climate change on yield of irrigated and rainfed rice and maize crops in the coastal area in the PRECIS A1b 2030 scenario. The values are percentage of deviation from current yields. Each dot represents the crop area and its distribution.

Spatial and temporal variations exist for temperatures in the coastal region. During kharif season, the upper west coast areas have seasonal mean minimum and maximum temperature regimes of about 23/30°C (23°C $T_{\min}$/30°C $T_{\max}$), while the middle west coastal region has a temperature regime of 18/27°C. The lower west coastal region has a temperature regime of 22/30°C. On the other hand, in the east coast seasonal mean minimum and maximum temperature was about 26/33°C. Seasonal maximum temperatures were slightly higher (35°C) in coastal Tamil Nadu, whereas they were slightly lower in north coastal Andhra Pradesh and Orissa (32°C). In the west coast, kharif rainfall ranged from 2000 to 4000 mm, while in the east coast it ranged from 500 to 1500 mm, with south coastal Tamil Nadu receiving about 500 mm rainfall. The projected increase in seasonal mean minimum temperature during kharif is about 1°C in the west coast, except in southern Kerala where it is likely to increase by 1.5°C. Similar increase is projected for the east coast from the south up to the coast of Andhra Pradesh. However, the Orissa coast is projected to have slightly less increase in temperature, i.e. by about 1°C in the 2030 scenario. Kharif seasonal rainfall is projected to increase more in the west coast (up to 20%), while in east coast it is likely to decrease by up to 15%, except in northern coast of Andhra Pradesh and the Orissa coast, where it is projected to increase by up to 10%.

Reasons for the projections obtained in the western coastal region are almost similar as explained for changes in the Western Ghats. In other areas of the coastal region, projected increase in yield of rainfed rice and maize is closely linked to the likely increase in rainfall in these regions. Increase in rainfall in areas where current rainfall is limiting the productivity will benefit the rainfed crops. Whereas irrigated maize and rice are likely to lose in majority of the east coast belt mainly due to increase in temperature. However, in coastal Orissa the projected increase in irrigated rice is possibly due to lesser increase in temperatures in the 2030 scenario, as mentioned earlier. Marginal increase in rainfall may not hamper the sunshine period in this region, providing ample scope for the plants to carry on photosynthetic process, thus

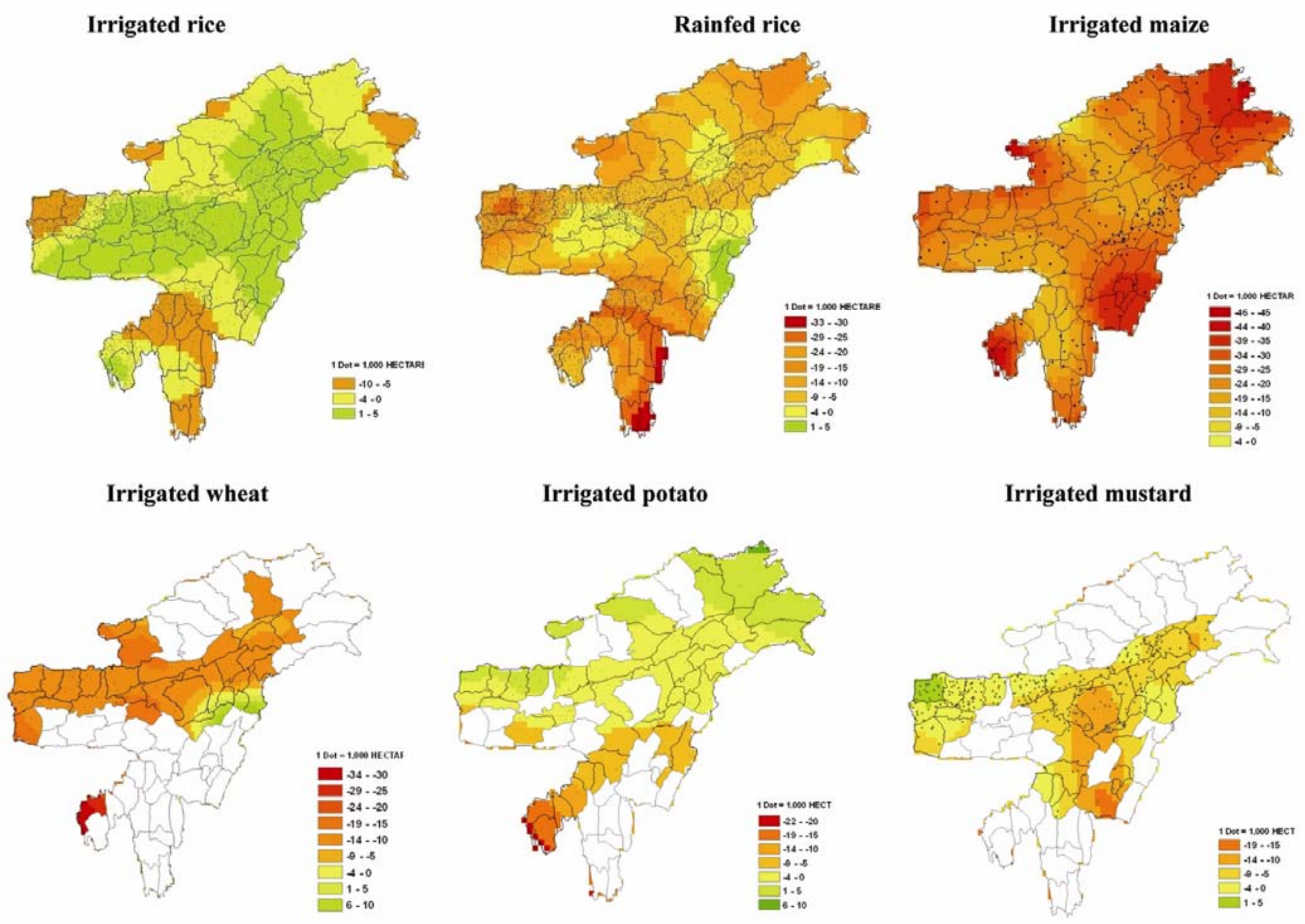

Figure 4. Impact of climate change on yield of irrigated rice, maize, wheat, potato and mustard crops and of rainfed rice in the northeastern region in the PRECIS A1b 2030 scenario. The values are percentage of deviation from current yields. Each dot represents the crop area and its distribution.

benefiting the rice yields in elevated CO_2 conditions. Currently, the productivity of irrigated maize is higher than that of rainfed maize. Maize, being a C4 crop, is able to accumulate higher biomass even at current CO_2 levels due to higher photosynthetic efficiency and thus yields high when water and other nutrients are not limiting. On the other hand, growth and yield of rainfed maize is limited by water and nutrients. In the 2030 scenario, higher temperature and reduced sunshine because of more rains may limit the biomass production and yield compared to the baseline conditions. Even though C4 crops do not get direct benefit of elevated CO_2 for higher photosynthetic rates, they may benefit through leaf water balance[19].

Probable impacts of climate change on agriculture in NE region in the 2030 scenario

Analysis indicates that the climate change may impact the irrigated rice yields by about –10% to 5%, with majority of the NE region benefiting up to 5% in the A1b 2030 climate scenario (Figure 4). On the other hand, the impacts on rainfed rice are likely to be in the range –35% to 5%, with a large area losing by about 10%. Irrigated maize yields are projected to reduce by about 40%. In case of rabi season crops, wheat yields are projected to reduce by up to 20%. Potato yields are likely to marginally increase up to 5% in the upper parts of the NE region due to climate change, but in the central parts projected yield loss is about 4%, and in southern parts of the region the negative impacts will be much higher. Irrigated mustard crop is also projected to lose yields up to 10% in majority of the areas.

The NE region has a mean minimum and maximum kharif seasonal temperature regime of 23/31°C, with the southern part being slightly cooler. However, this region has a high variability for rainfall in a range 500–4000 mm. Majority of the NE region receives about 1000–2000 mm of rainfall during the kharif season. The rabi seasonal mean minimum and maximum temperature regimes are about 9/24°C. Most of the NE region receives about 200 mm of winter rainfall as well. Projected increase in minimum and maximum temperature during kharif season is about 2°C in the 2030 scenario. However, in the southern parts of the NE region, maximum temperature is projected to increase by about 1.5°C. The kharif seasonal rainfall is likely to reduce by about 10% in majority of the NE region. On the other hand, during rabi projected increase in temperature is about 2.5°C and rainfall also is projected to increase by about 10%.

Variability in response of irrigated and rainfed rice in the NE region mainly could be because of differences in the quantity of fertilizers applied apart from the climatic factors. Rainfed rice will not be able to get the CO_2 fertilization benefits at the present input status since rainfall will not be a limiting factor in this region despite the projected 10% reduction in kharif rainfall. In higher temperature conditions, crop duration is reduced resulting in less time for biomass accumulation and thus reduced yields. In the case of irrigated rice, these negative effects of rise in temperature seems to be adequately compensated in high CO_2 concentrations, at least till the temperature regimes reach supra-optimal levels. In the case of rabi crops, yield loss in wheat and mustard will be mainly because of temperature rise-driven reduced crop duration, and high temperatures during the grain-filling period. In the case of potato, slight increase in winter temperatures in the NE region will benefit the crop in regions where current winter temperatures are very low.

The analysis indicates that spatial variations in projected impacts of climate change are mainly due to variations in baseline temperature regimes, projected increase in temperatures, baseline rainfall, projected changes in rainfall, crop and crop management. Areas with projected supra-optimal temperatures, reduced rainfall in areas receiving already less rainfall and increased rainfall in already high rainfall zones (causing reduced sunshine duration) are likely to lose. On the other hand, reduction in rainfall in high-rainfall zones can in fact benefit the crops.

This study suffers from typical limitations and uncertainties of using crop models for impact assessment of climate change. Some of the key factors are – no consideration of future socio-economic trends, including land use, technological improvements, and changes in water, soil fertility, pests and disease scenarios. Crop variety, crop management practices and soil fertility levels considerably vary even from one field to another, and also from farmer to farmer. These vary in future climatic conditions as well. However, due to non-availability of data at finer resolution for current conditions and with no modelled data for future conditions, it is assumed that the general regional management practices for crops, pests and diseases in future also will be similar to the current practices. Soil fertility is assumed to remain the same as it is at present. This assessment is done for business-as-usual scenario and therefore, area under crops is also assumed to remain the same, whereas the farmer is assumed to have optimized his variety and will grow the same variety unless new, improved varieties are provided. In addition, in the absence of greater details, it has been assumed that future inter-annual climatic variability and rainfall distribution will remain as in the baseline period, a situation that may not necessarily be true in the long term. However, in the scenario analysis, increase in climatic extremes is considered to a certain extent. Use of climate scenario outputs from a single climate model is also a source of uncertainty. Therefore, uncertainties in such analysis exist due to inheritance of uncertainties right from the greenhouse gas emission concentrations, consequent changes in temperature and rainfall (as modelled by the GCMs and RCMs) and inherent limitations of the crop simulation models. A greater and detailed understanding of crop response to various weather parameters, alone and in combination, under different management and soil conditions is required. There is also a need to run more regional climate models at finer resolution for improved analysis. Efforts should be initiated to develop the database required for detailed and integrated impact assessments. In spite of these limitations and uncertainties, this analysis provides a vital clue about the possible impacts on crops in these areas for enabling better preparedness to reduce the negative impacts. Thus, it can be concluded that the climate change in the Western Ghats, coastal districts and NE region is projected to significantly affect crop production. The impacts are crop-specific and simple adaptation strategies such as change in variety and altered agronomy, high input delivery and use efficiency can offset the negative impacts of climate change.

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1. Rosenzweig, C. and Parry, M. L., Potential impact of climate change on world food supply. *Nature*, 1994, **367**, 133–138.
2. Fischer, G., Shah, M. and van Velthuizen, H., *Climate Change and Agricultural Vulnerability*, International Institute for Applied Systems Analysis, Laxenburg, Austria, 2002.
3. Parry, M. L., Rosenzweig, C., Iglesias, Livermore, A. M. and Fischer, G., Effects of climate change on global food production under SRES emissions and socio-economic scenarios, *Global Environ. Change*, 2004, **14**, 53–67.
4. IPCC, *Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability*, Summary for policymakers. Inter-Governmental Panel on Climate Change, 2007.
5. Long, S. P., Ainsworth, E, A., Leakey, A. D. B. and Morgan, P. B., Global food insecurity. Treatment of major food crops with elevated carbon dioxide or ozone under large-scale fully open-air conditions suggests recent models may have overestimated future yields. *Philos. Trans. R. Soc. London Ser. B*, 2005, **360**, 2011–2020.
6. Aggarwal, P. K. and Sinha, S. K., Effect of probable increase in carbon dioxide and temperature on productivity of wheat in India, *J. Agric. Meteorol.*, 1993, **48**, 811–814.
7. Rao, G. D. and Sinha, S. K., Impact of climatic change on simulated wheat production in India. In *Implications of Climate Change for International Agriculture: Crop Modelling Study* (eds Rosenzweig, C. and Iglesias, I.), EPA, USA, 1994, pp. 1–10.
8. Lal, M., Singh, K. K., Rathore, L. S., Srinivasan, G. and Saseendran, S. A., Vulnerability of rice and wheat yields in NW – India

to future changes in climate. *Agric. For. Meteorol*., 1998, **89**, 101–114.

9. Saseendran, S. A., Singh, K. K., Rathore, L. S., Singh, S. V. and Sinha, S. K., Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climatic Change*, 2000, **44**, 405–414.
10. Aggarwal, P. K. and Mall, R. K., Climate change and rice yields in diverse agro-environments of India. II. Effect of uncertainties in scenarios and crop models on impact assessment. *Climatic Change*, 2002, **52**, 331–343.
11. Mall, R. K. and Aggarwal, P. K., Climate change and rice yields in diverse agro-environments of India. I. Evaluation of impact assessment models. *Climatic Change*, 2002, **52**, 315–330.
12. Aggarwal, P. K., Global climate change and Indian agriculture: impacts, adaptation and mitigation. *Indian J. Agric. Sci*., 2008, **78**(11), 911–919.
13. Samra, J. S. and Singh, G., *Heat Wave of March 2004: Impact on Agriculture*, Indian Council of Agricultural Research, New Delhi, 2004, p. 32.
14. Samra, J. S. and Singh, G., *Drought Management Strategies*, Indian Council of Agricultural Research, New Delhi, 2002, p. 68.
15. Byjesh, K. S., Naresh Kumar, S. and Aggarwal, P. K., Simulating impacts, potential adaptation and vulnerability of maize to climate change in India. *Mitig. Adapt. Strat. Global Change*, 2010, **15**, 413–431.
16. Srivastava, A. S., Naresh Kumar, S. and Aggarwal, P. K., Assessment on vulnerability of sorghum to climate change in India. *Agric. Ecosyst. Environ.*, 2010, **138**, 160–169.
17. Bujarbarua, P. and Baruah, S., Vulnerability of fragile forest ecosystem of North East India in context with the global climate change: An ecological projection. In IOP Conference Series: Earth and Environmental Science, 2009, vol. 6(7), pp. 1–4.
18. Aggarwal, P. K. *et al*., InfoCrop: A dynamic simulation model for the assessment of crop yields, losses due to pests, and environmental impact of agro-ecosystems in tropical environments. II. Performance of the model. *Agric. Syst*., 2006, **89**, 47–67.
19. Ghannoum, O., Von Caemmerer, S., Ziska, L. H. and Conroy, J. P., The growth response of C4 plants to rising atmospheric CO_2 partial pressure: a reassessment. *Plant Cell Environ*., 2000, **23**, 931–942.
20. Aggarwal, P. K., Joshi, P. K., Ingram, J. S. and Gupta, R. K., Adapting food systems of the Indo-Gangetic plains to global environmental change: Key information needs to improve policy formulation. *Environ. Sci. Policy*, 2004, **7**, 487–498.
21. Boomiraj, K., Chakrabarti, B. Aggarwal, P. K., Choudhary, R. and Chander, S., Assessing the vulnerability of Indian mustard to climate change. *Agric. Ecosyst. Environ*., 2010, **138**, 265–273.
22. Singh, J. P., Govindakrishnan, P. M., Lal, S. S. and Aggarwal, P. K., Increasing the efficiency of agronomy experiments in potato using InfoCrop-POTATO model. *Potato Res*., 2005, **48**, 131–152.
23. Naresh Kumar, S., Kasturi Bai, K. V., Rajagopal, V. and Aggarwal, P. K., Simulating coconut growth, development and yield using InfoCrop-coconut model. *Tree Physiol.*, 2008, **28**, 1049–1058.
24. Bandyopadhyay, A., Bhadra, A., Raghuwanshi, N. S. and Singh, R., Estimation of monthly solar radiation from measured air temperature extremes. *Agric. For. Meteorol*., 2008, **148**, 1707–1718.
25. Ainsworth, E. A. and Long, S. P., What have we learned from 15 years of free-air CO_2 enrichment (FACE)? A meta-analytic review of the response of photosynthesis, canopy properties and plant production to rising CO_2. *New Phytol*., 2005, **165**, 351–372.

ACKNOWLEDGEMENTS. We thank NATCOM, INCCA and the Ministry of Environment and Forests, Government of India, for involving us in the impact assessments and making available the climate scenarios data from IITM, Pune.