Abstract

Food production in India (having one-sixth of the world population) is already affected by changing climate and is expected to accelerate in the future due to an increase in temperature, change in rainfall pattern, and increased frequency and intensity of extreme events. India is highly vulnerable to the impacts of climate change because of high population density, large agricultural workforce and limited adaptive capacity. Furthermore, increasing population (from current levels of ~1.3 to ~1.65 billion by 2060) and consumption growth coupled with climate change will increase food security risk. With these underlying uncertainties and challenges, it becomes imperative to assess the impact of global warming-related climate change on food production. However, most of the studies assessing the climate change impacts on agriculture are site-specific, use few coarse-resolution GCM data, and ignore farm management variability. Studies utilising GCM data lack in capturing the uncertainty in future projections because considered GCMs are significantly less in number. None of the studies in India have explored the potential strategies (e.g., geoengineering) to combat climate change in fragile ecosystems (e.g., Himalayas).

The research in this thesis focuses on understanding the impact of climate change on major crops of the two most vulnerable regions, the Himalayas (fragile ecosystem, rapid warming, and marginal adaptive capacity) and Indo-Gangetic plains (high population, already stressed natural resources and marginal adaptive capacity) of India. To begin with, we first evaluated four statistical downscaling techniques (QM, KNN_p, KNN and SVM-KNN) to be used in agriculture impact assessment. Coarse-resolution GCM data are not suitable to be directly used for agriculture-related impact assessment studies, especially for developing regions having diverse crop management practices. QM and KNN_p use rainfall to downscale rainfall. In contrast, KNN and SVM-KNN use large scale atmospheric variables (e.g., air temperature, specific humidity, wind speed, geopotential height at various pressure levels) to downscale rainfall. We evaluated the performance of the downscaling methods, their ability to capture annual rainfall amount, spatial pattern, seasonal and daily variability, extreme rainfall amount and some agriculture-specific metrics. We found that, overall, all the techniques perform (using correlation coefficient, root mean square error and mean absolute error) satisfactorily. SVM-KNN and KNN fail to capture the seasonal and daily variability and extremes of the monsoon (JJAS) rainfall, whereas QM outperforms all the other techniques for the same. Wet day fraction, wet spell length, average wet spell rainfall and dry spell length were used to evaluate the usefulness of these techniques in agriculture applications. QM performs best for the agriculture-specific metrics, and SVM-KNN and KNN significantly overestimate. Based on our analysis, we chose QM to downscale the GCM outputs and use it for further analysis in the subsequent chapters.

Next, the impact of global warming on land suitability of deciduous fruit over Himachal Pradesh was assessed using Hadley Global Environment Model 2 - Earth System (HadGEM2-ES) and Max Planck Institute Earth System Model (MPI-ESM) under RCP4.5 from CMIP5. A corresponding stratospheric geoengineering scenario (G3 from GeoMIP5), proposed to combat the harmful effects of global warming, was also assessed for the same models. We used the period 2055–2069 (with the highest geoengineering forcing [switched-on]) and the period 2075–2089 (beginning five years into the termination phase [switched-off]) for analysis. We found that stratospheric geoengineering would suppress the increase in temperature under RCP4.5 scenario to some extent during both switched-on and switched-off periods. However, if the geoengineering were terminated, the rate of temperature increase would be higher than RCP4.5. The agroclimatically suitable area is projected to shift north- eastwards (to higher elevations) under RCP4.5 as well as G3 during both periods. However, geoengineering would restrict the shift during the switched-on period, and areas of Shimla and Mandi districts (most suitable under the current climate) would not be lost due to global warming. Even during the switched-off period, before the climate returned to RCP4.5 levels, the above areas would, although to a lesser extent, have reduced harmful climate effects from global warming. However, the area of suitable land (the intersection of suitable soil and agroclimatic suitability) would decrease in both periods for RCP4.5 and G3, because the high-elevation regions that become agroclimatically suitable are mostly rocky (unfit for cultivation). Geoengineering could benefit deciduous fruit production by reducing the intensity of global warming. However, if geoengineering were terminated abruptly, the rate of temperature change would be quite high, leading to a rapid change in land suitability and might result in total crop failure in a shorter period than RCP4.5.

In the next part of the thesis, the impact of climate change on Kharif season rice using more than a thousand crop-climate scenarios in Uttar Pradesh was carried out. Uttar Pradesh is divided into nine agroecological zones (AEZs) based on climate and soil. The study area of Uttar Pradesh has a total of 342 grids of 25 km x25 km grid-spacing, and each AEZ contains a given number of grids. A total of 1152 (16 x 4 x 2 x 3 x 3) experiments were designed using a combination of planting dates (3), rice cultivars (4), GCMs (16), irrigation conditions (2), and CO_2 concentration (3; historical, Shared Socio-economic Pathway 245 [SSP245] and SSP585) for a total of 342 grids. A gridded framework was designed to run the site-specific CERES-Rice model in a gridded environment. The simulations were carried out by forcing CERES-Rice with bias-adjusted and downscaled CMIP6 GCMs for historical, SSP245 and SSP585. In addition, the CO_2 fertilization effect is quantified by performing sensitivity experiments that include forcing CERES-Rice with a constant CO_2 value representative of 2005 (average of 1995-2014) and climates from SSP245 and SSP585 for all the three future periods for one planting scenario. The CERES-Rice simulations were performed for the historical (1995-2014) and three future periods (2030s [2026-2035], 2050s [2046-

2055], and 2090s [2090-2099]) for the two SSPs. Phenology (anthesis and maturity), irrigation amount, crop evapotranspiration (ET), crop transpiration (EP), soil evaporation (ES), yield and water use efficiency (WUE) were evaluated and assessed for all AEZs.

Next, we evaluated CERES-Rice outputs for historical runs (1995-2014), forced with bias-adjusted and downscaled GCM climate with IMD-forced simulations. The output variables were averaged for early, mid, and late planting (25 June, 5 July, and 15 July), four cultivars, and aggregated for each AEZ for irrigated and rainfed rice. We found that the CERES-Rice simulations are dependent on input climate variables. Bias-adjusted and downscaled data produce match well with IMD data, yet residual biases in the frequency, intensity, and distribution of rainfall affect the related crop model outputs. Irrigation requirement and soil moisture (that affects ES, EP, ET, irrigation, yield and WUE) heavily depend on rainfall, hence their performance is affected. The uncertainties are higher in rainfed rice because it solely depends upon rainfall for crop water requirement, unlike irrigated rice, which is not limited by water availability. The model performance was found to vary with planting dates and AEZs.

Next, the impact of climate change under SSP245 and SSP585 was assessed for irrigated and rainfed rice for all the planting seasons. Results based on the multi-model mean (MMM) of 16 GCMs project increased rainfed rice yield in AEZs of western Uttar Pradesh due to increased rainfall, however, in eastern Uttar Pradesh, yield decreases under both SSPs. Irrigated rice yield decreases in all AEZs under both SSPs due to increase in temperature and decrease in the length of growing period, and by 2090s the reduction is up to 20%. For irrigated rice, lowest decrease in yield is in early planting, and for rainfed rice, highest increase in yield is in early planting. Irrigation decreases monotonically from early to the end of the century due to increased rainfall and a decrease in crop ET. The reduction in crop ET is associated with reduced vapour deficit (due to increased rain) and elevated CO_2 (reduced stomata opening). Water use efficiency (WUE) increases for both irrigated and rainfed rice from 2030s to 2050s and decreases by 2090s. The elevated CO_2 concentration increases rice yield for both rainfed and irrigated conditions. However, the combination of increased rainfall and CO_2 levels seems to be more beneficial for rainfed rice than irrigated rice. The CO_2 fertilization effect in rainfed rice is not spatially uniform as that in irrigated rice. The highest increase in rainfed rice yield due to elevated CO_2 is projected over semi-arid and dry sub-humid AEZs of Uttar Pradesh. Overall, our analysis finds that rainfed rice yield is projected to increase in western Uttar Pradesh, whereas decrease in eastern Uttar Pradesh under climate change. Irrigated rice yield is projected to decrease in all the AEZs of the state under climate change.