Identification of the most appropriate adaptation for rice and wheat in the face of climate change in eastern India

Madhuri Dubey, Ashok Mishra and Rajendra Singh
Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, WB 721302, India
*Corresponding author. E-mail: amishra@agfe.iitkgp.ac.in

ABSTRACT

The changing climate affects natural resources that impart a negative impact on crop yield and food security. It is thus imperative to identify agro-climate wise, area-specific adaptation options to ensure food security. This study, therefore, evaluated some feasible adaptation options for two staple food grain crops, rice and wheat, in different agro-climatic regions (ACRs) of Eastern India. Alteration in transplanting date, seedling age, and fertilizer management (rate and split of fertilizer) for rice; and sowing date, fertilizer management, and deficit irrigation scheduling for wheat, are assessed as adaptation options. The crop environment and resource synthesis (DSSAT) model is used to simulate the crop yield using different plausible adaptation options to projected climate scenarios. Findings show that shifting transplanting/sowing date, and nitrogen fertilizer application at 120% of recommended nitrogen dose with four splits could be an effective adaptation for rice and wheat crops. Results also emphasize that transplanting of 18 days older seedlings may be beneficial in rice cultivation. In contrast, irrigation at a 30–40% deficit of maximum available water would sustain the wheat yield under climate change conditions. This study suggests the best combination of adaptation options under climate change conditions in diverse ACRs, which may assist agriculturists in coping with climate change.

Key words: adaptation options, agro-climate region, CERES, climate change, rice, wheat

HIGHLIGHTS

- Feasible adaptation options for rice and wheat to lessen climate change impact are evaluated.
- Shifting transplanting/sowing date, N-application at 120% of recommended dose with four splits have shown sustainable adaptability for rice and wheat in the future.
- Transplanting of 18 days older seedlings may reduce the rice yield decline in the future.
- Irrigation at 30–40% deficit may sustain the wheat yield under climate change.

INTRODUCTION

Increasing stress on agriculture due to erratic climate conditions is becoming inevitable in different regions of the world (Easterling et al. 2007; Rosenzweig & Tubiello 2007; Sauchyn & Kulshreshtha 2008; Reidsma et al. 2010). Climate change can alter the biophysical media of crops and crop growth, consequently affecting agricultural productivity. Growing rice and wheat, two staple crops of the majority of the people worldwide, appears to be susceptible to future climate change conditions (Fischer et al. 2002; Anwar et al. 2007; Eyshi Rezaie & Bannayan 2012). Several investigations show that rice and wheat yield has reduced in the past and is likely to further decrease in the wake of climate change (Zacharias et al. 2014; Chun et al. 2016; Rao et al. 2016; Kontgis et al. 2019). It is essential to maintain/increase crop production to ensure food security under adverse climate change conditions (Stocker et al. 2013). The increase in the crop productivity is only possible by implementing appropriate adaptation options to alleviate the negative impact of climate change (Rosenzweig & Tubiello 2007).

Various adaptation options, such as changes in the sowing date, fertilizer rate, seed rate, crop rotations, irrigation management, and use of cultivar have been evaluated over the different regions of the world to lessen the adverse impact of climate change (Smit & Skinner 2002; Tubiello et al. 2002; Rosenzweig & Tubiello 2007; Turral et al. 2011; Debnath et al. 2021). Based on the findings of these investigations, it can be concluded that the potential of adaptation options differs with location,
crops, and magnitude of climate change. For instance, Bai et al. (2016) showed that modern cultivars and agronomic management (cultivar renewal, planting density, and fertilizer management) play a key role in increasing the yield to compensate for the negative impact of climate change on rice and wheat yield in China. Shrestha et al. (2016) analysed the effect of shifting in transplanting date, supplemental irrigation, and nitrogen management for rice in Central Vietnam. They deduced that supplemental irrigation is more beneficial than other options. Another study by Banerjee et al. (2016) found that sowing time and nutrient management are adequate for good harvest, but older rice seedlings and a high seed rate of mustard are less effective in Eastern India. Selection of cultivar based on growing period and heat tolerance could be a vital adaptation option against the elevated CO2 and temperature in the Indian region (Byjesh et al. 2010; Satapathy et al. 2014). Mishra et al. (2013) used short-term rainfall prediction as a soft adaptation to mitigate the adverse effects of climate change in North-East India. Some studies evaluated the impact of a shift in planting date on yield and water productivity and concluded that change in planting date could significantly improve both the aspects (yield and water productivity) under changing climate conditions (Laux et al. 2010; Dharmarathna et al. 2014; Chun et al. 2016; Li et al. 2017).

Prediction of crop response under different management strategies and climate conditions is inextricable and performing field experiments trials considering all factors turns out to be progressively perplexing and pricey. For this purpose, crop models are widely accepted tools to simulate crop growth and yield under climate change conditions with varying management strategies (Parry et al. 2005; Rosenberg 2010; Shelia et al. 2019). Crop Environment and Resource Synthesis (CERES) model, embedded in Decision Support System for Agrotechnology Transfer (DSSAT), is a robust decision support system (Jones et al. 2003; Timsina & Humphreys 2006). CERES requires location-specific soil properties, crop management details, and weather information to simulate crop yield. Future climate projections of rainfall, temperature, and solar radiation are essential inputs to the crop model to predict the crop yield under climate change conditions. Global climate models (GCMs) are developed to generate the future projection of climate variables worldwide and are successfully used for different climate change impact and adaptation studies.

Most of the previous investigations attempted to examine various adaptation options using either a fixed change in weather variables or a few climate models with one or two projected climate scenarios. In practice, this approach may mislead regarding the magnitude/extent of climate change, leading to erroneous adaptation strategy decisions. Furthermore, evaluation of different adaptation options for rice and wheat crops over different agro-climatic regions (characterized by different climate and soil conditions) covering eastern Indian is still lacking. Therefore, the objective of this study is to evaluate feasible adaptation options to reduce the negative impact of climate change on rice and wheat crops using eight GCMs in different agro-climate regions (ACRs) of West Bengal State in eastern India.

STUDY AREA
The West Bengal state of India (lying between 21°31’N and 27°14’N latitude and 85°91’E and 89°53’E longitude) is selected as the study area to evaluate the different adaptation options for rice and wheat (Figure 1). West Bengal is divided into six ACRs based on varying soil and climate conditions, namely, North Hill Region (NHR), Teesta Terai Region (TTR), Vindhyachal Alluvial Region (VAR), Gangetic Alluvial Region (GAR), Red Laterite Region (RLR), and Coastal Saline Region (CSR). The rainfall in the area varies between 1,100 mm (red and laterite region) and 3,500 mm (hilly region). Similarly, the average temperature in the study area varies between 8.4 °C (a minimum value for the hilly region) and 37 °C (a maximum value for the red and laterite region). West Bengal is an agrarian state where rice, wheat, jute, tea, potato, sugarcane, pulses, and oilseeds are the major crops.

DATA USED
Observed and future climate data
Observed rainfall, maximum temperature, and minimum temperature were collected from India Meteorological Department (IMD), Pune, from 1976 to 2005. Rainfall and temperature data were available at 0.25° and 1°, respectively. Since observed solar radiation was unavailable, it is collected from National Oceanic and Atmospheric Administration (www.noaa.com) at 0.3° spatial scale and assumed as observed solar radiation (Gupta & Mishra 2019). Further, all the weather variables were rescaled to 0.25°×0.25° spatial scale.

The climate projections used in this study were collected and processed under the investigation performed by Dubey et al. (2021) for the same study area. Climatic projections of rainfall, temperatures (maximum and minimum), and solar radiation
from eight GCMs under CMIP5 (Coupled Model Intercomparison Project-5; cmipcmdi.llnl.gov/cmip5/data_portal.html) were used in this study. The climate data were rescaled to 0.25° × 0.25° spatial scale using bilinear interpolation, and bias corrected using the quantile mapping method (Dubey et al. 2021). The GCM data are available for the historical period (1976–2005) and future period (2006–2100) for four Representative Concentration Pathways (RCPs) scenarios (RCP2.6, 4.5, 6.0, and 8.5).

CERES model
CERES model embedded in DSSAT (Hoogenboom et al. 2012) platform for rice and wheat is used in this study. CERES is the most widely used, extensively tested, and reliable model that has the potential to simulate crop development/growth, biomass, grain yield, leaf area index, and water and nitrogen dynamics under varying soil, management (sowing, fertilizer, and irrigation), and climate conditions (Hoogenboom et al. 1991; Mubeen et al. 2020). The minimum required inputs to the CERES model are weather (rainfall, maximum and minimum temperature, and solar radiation), soil (layer-wise particle size distribution, bulk density, maximum water holding capacity, field capacity, and permanent wilting point), crop management practices (seed rate, sowing method, irrigation and fertilizer input, crop cultivar) information, and genetic coefficients of the crop cultivar. Genetic coefficients demonstrate the genetic potential of the respective cultivar irrespective of every environmental limitation, such as weather, soil, and so on, by simulating the yield of various cultivars in different conditions, and it is conceivable to choose the one(s) that best utilize the accessible resources. Different cultivars have a certain set of genetic parameters for each model. A description of genetic coefficients used in the CERES model for rice and wheat is given in Jones et al. (2003).
CERES calibration and validation
Calibrated and validated CERES model for rice (cultivar-IR36) and wheat (cultivar-Sonalika) by Dubey et al. (2021) for West Bengal region is used to simulate the yield to identify the most suitable adaptation options under climate change conditions. The performance of the CERES model was further evaluated by comparing district wise observed yield with IMD weather and bias-corrected GCMs (ensemble) simulated yield for rice and wheat over different districts of West Bengal. Observed yield for different districts of West Bengal was collected from an e-resource of socio-economic statistical information/data of India (www.indiastat.com) for the period of 1987–2005. The model performance was tested using root mean square error (RMSE), normalized root mean square error (nRMSE), and index of agreement (d) (Willmott 1982). The performance measures are expressed as follows:

Root mean square error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (X_s - X_o)^2}$$

where $X_s$ and $X_o$ are simulated and observed yield, and $N$ is the number of observations.

Normalized root mean square error (nRMSE)

$$n\text{RMSE} = \frac{\text{RMSE}}{\sigma}$$

where $\sigma$ is the standard deviation.

Index of agreement (d)

$$d = 1 - \frac{\sum_{i=1}^{N} (X_o - X_s)^2}{\sum_{i=1}^{N} (|X_s - X_o| + |X_o - X_s|)^2}$$

where $X_o$ is the average of observed yield for $N$ number of observations.

Evaluation of the most appropriate adaptation options
The methodology to evaluate the suitability of adaptation options for rice and wheat crop is presented in Figure 2. The CERES model was validated by simulating the crop yield using IMD weather and GCMs output for the historical period (1987–2005). Further, the validated model is used to evaluate the most suitable adaptation options. A few feasible adaptation options, namely, changing planting/sowing date, nitrogen dose, nitrogen split, seedling age, and deficit irrigation scheduling are evaluated for rice and wheat crops over different ACRs of West Bengal through modelling analysis. Crop model simulations were performed using selected adaptation options for three future periods 2006–2035 (2020s), 2036–2065 (2050s), and 2066–
2095 (2080s) under four RCPs (2.6, 4.5, 6.0, and 8.5). These simulations were performed for different grids covering the study area. To obtain crop yield for different ACRs, weighted average of the grid-wise yield covering individual ACR was determined. The change in simulated yield using different adaptation options, with respect to the historical yield, was determined to analyze the effect of adaptation options on crop yield. The adaptation options showing a maximum decrease in the negative effect of climate change effect have been identified as the best adaptation option. To simulate the rice yield for the historical period, fixed date of transplanting, i.e., 21 June, 21 days older seedling, recommended nitrogen dose (RND) of 120 kg/ha, and three splits of N-fertilizer at basal, tillering, and panicle initiation stage were used. In the case of wheat yield simulation for the historical period, fixed date of sowing, i.e., 27 November, recommended dose of N-fertilizer (100 kg/ha), and three splits of N-fertilizer at sowing, crown root initiation, and panicle initiation stages were considered. Irrigation was done at a 50% deficit of maximum available water (MAW).

A wide range of transplanting dates from 15 June to 15 August at ten-day intervals was used for yield simulation to evaluate the effect of shifting transplanting dates on rice yield under climate change conditions. Furthermore, simulations were performed using seedling ages of 18, 21, 25, and 30 days to evaluate the effect of seedling age on rice yield under climate change conditions. For the wheat crop, varying sowing dates from 1 November to 30 December at 10-day intervals were evaluated to identify the optimum sowing time under climate change conditions. Additionally, the future wheat yield was simulated by scheduling irrigation application at 20, 30, 40, 50, and 60% deficit to determine the best irrigation strategies. In addition to the adaptation options mentioned above, different N-fertilizer rates and number of split of N-dose were also investigated for both the crops under future climate change conditions. Fertilizer application at 60% (N60), 80% (N80), 100% (N100), 120% (N120), and 140% (N140) of RND, and two, three, and four splits of RND were used to analyse the effect on rice and wheat yields.

RESULTS AND DISCUSSION
CERES validation over West Bengal
Calibrated and validated CERES model was tested by simulating rice and wheat yield over the 19 districts of West Bengal and performance measures of the model are presented in Tables 1 and 2. These tables show the comparison among the observed yield, IMD weather simulated yield, and GCMs ensemble yield for rice and wheat crops. In addition, a comparison of yield at an annual scale among the aforementioned yields is also shown in Figure 2 for the district showing least error to simulate the rice and wheat yield. For rice crop (Table 1), d-stat varies from 0.85 to 0.96 and 0.82 to 0.94 for IMD weather simulated yield and GCMs ensemble yield, respectively. RMSE ranges from 247 to 568 kg/ha for IMD weather simulated yield and from 258 to 735 kg/ha for GCMs ensemble yield. Moreover, nRMSE varies from 1.3 to 2.8 for IMD weather simulated yield and 1.5 to 6.5 for GCMs ensemble yield. The minimum error is observed for North 24 Parganas district as IMD weather simulated yield and GCMs ensemble yield are close to observed yield (Figure 3(a)).

In the case of wheat crop (Table 2), d-stat ranges from 0.76 to 0.95 and 0.75 to 0.90, and RMSE varies from 337 to 737 kg/ha and 342 to 800 kg/ha for IMD weather simulated yield and GCMs ensemble yield, respectively. In addition, nRMSE varies from 0.8 to 1.7, and 1.3 to 2.0 for IMD weather simulated yield and GCMs ensemble yield, respectively. The lowest difference between observed and simulated yield (IMD weather and GCMs ensemble yield) is obtained for the Cooch Behar district (Figure 3(b)).

ADAPTATION ANALYSIS FOR RICE
Transplanting date
To identify the most appropriate rice transplanting date, different transplanting dates from 15th June to 15th August, at ten-day intervals, are considered to simulate yield in six ACRs of West Bengal. The results are presented in Figure 4. Results indicate that transplanting on 5th July in NHR would be beneficial as rice yield is predicted to increase in the future under RCP2.6 (4.4%), 4.5 (3.7%), and 6.0 (2.2%). Moreover, the least yield reduction is shown in this zone under RCP8.5 (−2.9%) by transplanting on 5th July. In TTR, the maximum increment in yield is anticipated as 7.3, 6.1, and 5.6% in future under RCP2.6, 4.5, and 6.0, and the lowest reduction is achieved under RCP8.5 (−1.6%) with transplanting on 15th July. In VAR and RLR, transplanting around 5th August would be able to reduce the negative impact of climate change. The maximum yield enhancement may be achieved as 14.5, 10.6, and 7.9% in VAR and 16.2, 14.8, and 9.4% in RLR in future under RCP2.6, 4.5, and 6.0, respectively. However, the lowest yield decline is expected as −7.4 and −8.9% at the end of the century under RCP8.5 with
transplanting on 5th August. In GAR, transplanting on 15th July would be favourable under climate change conditions as yield is expected to increase by 7.3, 5.4, and 2.5% in future under RCP2.6, 4.5, and 6.0, respectively, with the minimum yield reduction in under RCP8.5 (−5.4%). Transplanting of rice on 25th July in CSR may increase yield by 13.7, 11.5, and 8.0% in future under RCP2.6, 4.5, and 6.0, respectively. While, the least reduction is anticipated as −7.3% by the end of the century under RCP8.5. Advancing rice transplanting date has also been reported to improve yield condition in eastern India under climate change by Krishnan et al. (2007). Change in transplanting date alters growth stages that allow the plant to develop adequately under varying temperature ranges (Dharmaratha et al. 2014; Chun et al. 2016; Li et al. 2017). Overall results indicated that VAR, RLR, and CSR regions have great potential to sustain yield by altering the transplanting date. It is noted that the potential of adaptation options to alleviate the negative impact of climate change on crop yield is more under RCP2.6 and RCP4.5 than under RCP6.0 and 8.5. This is due to the difference in scenario development assumptions which is based on the population, economic growth, energy consumption and sources, technological development, and land use (Stocker et al. 2013). RCP2.6 is the low emission scenario with radiative forcing at about 2.6 W/m² before 2100 and then decline and RCP4.5 is the moderate scenario without overshoot pathway to 4.5 W/m² before 2100. RCP6.0 is a stabilization scenario but without an overshoot pathway to 6 W/m² at 2100, whereas RCP8.5 is the highest emission scenario with radiative forcing leading to 8.5 W/m² in 2100.

Seedling age

Effects of seedling age on rice yield under climate change conditions over different ACRs of West Bengal are shown in Figure 5. It appears that rice yield tends to reduce more in most of the ACRs under future climate change conditions when the older seedlings are used. Results show that yield improvements is possible in NHR with 18-day-old seedlings under RCP2.6 (4.4%), RCP4.5 (2.8%), and RCP6.0 (0.8%), but the yield will reduce under the highest emission scenarios (−1.9%). In TTR, GAR, and CSR, younger seedlings would improve yield under RCP2.6 and 4.5, whereas yield would decline under RCP6.0 and 8.5. In VAR, yield is anticipated to increase only in the lowest emission scenarios, whereas in RLR, it is

| S.N. | Districts             | IMD            | Ensemble       |
|------|-----------------------|----------------|----------------|
|      |                       | RMSE | nRMSE | d-stat | RMSE | nRMSE | d-stat |
| 1.   | Darjeeling            | 416  | 2.1   | 0.89   | 575  | 3.6   | 0.83  |
| 2.   | Jalpaiguri            | 478  | 2.0   | 0.87   | 495  | 2.3   | 0.85  |
| 3.   | Cooch Behar           | 375  | 2.8   | 0.89   | 620  | 6.5   | 0.82  |
| 4.   | Uttar Dinajpur        | 264  | 1.4   | 0.96   | 373  | 1.5   | 0.91  |
| 5.   | Dakshin Dinajpur      | 344  | 2.4   | 0.87   | 495  | 2.6   | 0.87  |
| 6.   | Malda                 | 352  | 1.5   | 0.91   | 625  | 2.3   | 0.85  |
| 7.   | Murshidabad           | 371  | 1.7   | 0.90   | 567  | 2.7   | 0.86  |
| 8.   | Birbhum               | 276  | 2.1   | 0.95   | 354  | 2.5   | 0.89  |
| 9.   | Nadia                 | 323  | 1.7   | 0.94   | 412  | 1.9   | 0.87  |
| 10.  | Burdwan               | 290  | 2.1   | 0.90   | 353  | 2.6   | 0.88  |
| 11.  | Purulia               | 568  | 3.1   | 0.85   | 733  | 4.1   | 0.84  |
| 12.  | Bankura               | 270  | 2.0   | 0.94   | 387  | 2.4   | 0.91  |
| 13.  | Kolkata               | 300  | 1.9   | 0.84   | 343  | 2.2   | 0.87  |
| 14.  | Hooghly               | 318  | 2.4   | 0.91   | 465  | 2.5   | 0.85  |
| 15.  | Howrah                | 374  | 1.3   | 0.89   | 493  | 1.6   | 0.82  |
| 16.  | West Midnapur         | 432  | 1.4   | 0.86   | 576  | 1.9   | 0.81  |
| 17.  | East Midnapur         | 382  | 1.3   | 0.88   | 502  | 2.1   | 0.84  |
| 18.  | North 24 Parganas     | 247  | 1.6   | 0.96   | 258  | 1.9   | 0.94  |
| 19.  | South 24 Parganas     | 386  | 2.6   | 0.85   | 653  | 3.3   | 0.81  |
likely to reduce in all emission scenarios even with 18-day-old seedlings. Results unveiled that the highest yield increment (3.5%) is expected in TTR under future climate change with 18-day-old seedlings. These findings align with Banerjee et al. (2016), concluding that transplanting older seedlings under climate change conditions would result in rice yield reduction in West Bengal. Older seedling age leads to lower rice yield because more established seedlings experience the detrimental effect of prominent stem and root damage at the time of transplanting (Dizon et al. 1994; Reddy & Reddy 1994; Ashraf et al. 1999; Hundal & Kaur 1999; Kotera et al. 2004) which may reduce tillers and grain yield and lengthen the maturity period. However, older seedlings are used in lowland areas due to their capability to resist the weed and they can also manage with poor land and water management strategies (De Datta 1987; Poussin et al. 2003; Kotera et al. 2004).

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**Table 2** | Performance measures of CERES to simulate the historical wheat yield using IMD weather information and GCMs ensemble

| S.N. | Districts          | IMD         | Ensemble     |
|------|--------------------|-------------|--------------|
|      | RMSE   | nRMSE | d-stat | RMSE   | nRMSE | d-stat |
| 1.   | Darjeeling | 737  | 1.6   | 0.82   | 800   | 1.7   | 0.79   |
| 2.   | Jalpaiguri | 358  | 1.7   | 0.78   | 452   | 2.0   | 0.75   |
| 3.   | Cooch Behar | 294  | 1.4   | 0.95   | 342   | 1.4   | 0.90   |
| 4.   | Uttar Dinajpur  | 383  | 1.1   | 0.92   | 374   | 1.2   | 0.86   |
| 5.   | Dakshin Dinajpur | 326  | 1.6   | 0.89   | 374   | 1.5   | 0.85   |
| 6.   | Malda   | 352  | 1.2   | 0.87   | 460   | 1.5   | 0.82   |
| 7.   | Murshidabad | 372  | 1.2   | 0.89   | 441   | 1.3   | 0.84   |
| 8.   | Birbhum | 360  | 1.4   | 0.84   | 397   | 1.6   | 0.81   |
| 9.   | Nadia   | 363  | 1.4   | 0.93   | 358   | 1.3   | 0.87   |
| 10.  | Burdwan  | 355  | 1.5   | 0.94   | 511   | 1.9   | 0.88   |
| 11.  | Purulia | 544  | 1.4   | 0.76   | 590   | 1.5   | 0.72   |
| 12.  | Bankura  | 459  | 1.4   | 0.79   | 570   | 1.5   | 0.74   |
| 13.  | Kolkata | 478  | 1.6   | 0.77   | 497   | 1.8   | 0.73   |
| 14.  | Hooghly | 485  | 1.9   | 0.85   | 524   | 1.3   | 0.81   |
| 15.  | Howrah  | 487  | 0.8   | 0.78   | 571   | 1.6   | 0.76   |
| 16.  | West Midnapur | 365  | 1.7   | 0.87   | 395   | 1.3   | 0.83   |
| 17.  | East Midnapur | 528  | 1.7   | 0.77   | 589   | 1.5   | 0.74   |
| 18.  | North 24 Parganas | 337  | 1.6   | 0.90   | 426   | 1.6   | 0.86   |
| 19.  | South 24 Parganas | 393  | 1.0   | 0.88   | 509   | 1.6   | 0.85   |

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**Figure 3** | Comparison of observed yield with IMD weather simulated yield and GCMs ensemble yield for rice (a) for North 24 Parganas district, and wheat (b) for Cooch Behar district during 1987–2005.
Figure 4 | Percent change in rice yield with changing transplanting date in future compared to historical yield over six ACRs; (a) NHR, (b) TTR, (c) GAR, (d) VAR, (e) RLR, (f) CSR.
N-fertilizer rate

Percent change in rice yield for different application rates of N-fertilizer under climate change conditions with respect to historical yield in six ACRs is presented in Figure 6. In all ACRs, N60 showed the highest yield reduction, followed by N80, N100, and N120, and N140 of RND during the 2020s, 2050s, and 2080s under different scenarios. In NHR, TTR, and CSR, rice yield is anticipated to increase at N120 and N140 of RND level in future periods (the 2020s, 2050s, and 2080s).
Figure 6 | Percent change in rice yield with different N-fertilizer rates under climate change conditions with respect to the historical yield over six ACRs; (a) NHR, (b) TTR, (c) GAR, (d) VAR, (e) RLR, (f) CSR.
under RCPs 2.6, 4.5, and 6.0. However, the yield is predicted to reduce in the future despite higher N-fertilizer application under RCP8.5. In VAR, yield decline is expected at all nitrogen application levels except N140 of RND in the 2020s (1.2%) under RCP2.6. The lowest yield decline is noted as −2.5% by the end of the century among all RCPs with the same level of N-application. Yield simulation for RLR and GAR showed a slight improvement in yield during the 2020s and 2050s under RCP2.6 and 4.5; however, yield may reduce in the 2080s under RCP6.0 and 8.5. The most remarkable improvement in yield is feasible in TTR up to 8.1%, with RLR showing the highest yield loss (up to −16.2%) despite higher N-application. These findings are comparable to those of Bai et al. (2016), Banerjee et al. (2016), and Shrestha et al. (2016), who concluded that higher nitrogen dose might increase rice yield under future climate change conditions.

### Split of N-fertilizer

Different splits (two, three, and four splits) of RND were used to simulate rice yield under climate change conditions and percent change in yield during the 2020s, 2050s, and 2080s under different RCPs compared to historical period are presented in Figure 6. Results divulge that four splits of RND are more beneficial than two or three splits as they showed more significant yield improvement or lesser yield reduction compared to two and three splits under climate change conditions in all ACRs. It is evident from Figure 6 that in NHR and TTR, four splits of RND may improve rice yield in future under RCP2.6 and RCP4.5, whereas yield drop is expected under RCP6.0 and RCP8.5. In GAR, a small increase in yield is expected under RCP2.6 (1.3%), whereas, the minimum yield decline is anticipated under RCP4.5 (−0.3%), RCP6.0 (−2.5%), and RCP8.5 (−6.7%), when four splits of RND are used in yield simulation. In VAR and RLR, all splits (two, three, and four) resulted in yield decline in the 2020s, 2050s, and 2080s under different scenarios. In CSR, a slight increment in rice yield using four splits of RND is predicted in the 2020s (0.8%) and 2050s (0.1%) under RCP2.6. In this region, the minimum yield reduction is obtained in the future under RCP4.5 (−1.4%), RCP6.0 (−2.5%), and RCP8.5 (−7.9%). These findings align with Yoseftabar (2013) and Djaman et al. (2018), who noticed an increment in rice yield with higher splits of nitrogen fertilizer under climate change conditions.

### Combined effect of the best-suited adaptation options on rice

The identified best-suited adaptation options were combined to run the crop model to determine the overall potential of the feasible adaptation options for reducing the adverse effect of climate change. The most suitable transplanting dates are 5th July in NHR, 15th July in TTR and GAR, 5th August in VAR and RLR, and 25th July in CSR, which can alleviate the negative impact of climate change. Besides, 18-day seedling, N-fertilizer application at 120% of RND, and four split applications were chosen as the most appropriate adaptation option in all ACRs. An increase in fertilizer dose showed a continuous increment in yield in future periods; however, 120% of RND is chosen because of insignificantly increased yield response of higher nitrogen applications. Table 3 presents the percent change in yield during the 2020s, 2050s, and 2080s under different RCPs compared to historical period. Results indicate that early sowing of wheat leads to yield reduction over all the ACRs of West Bengal. Simulation results state that sowing of wheat on 30th November shows minimum yield decline in NHR in the range from −4.0 to −8.2%, −7.7 to −15.1%, and −10.7 to 16.8% in 2020s, 2050s, and 2080s under different scenarios. Similarly, in TTR, wheat sowing on 30th November reduces the least yield reduction ranging from −10.0 to −13.5%, −13.2 to −16.4%, and −12.4 to −24.0% in the respective period under different scenarios.
Wheat sowing in December would be beneficial in GAR under climate change conditions. Results showed that yield improvement is obtained between 5.8 and 8.1%, 1.9 and 6.9%, and 1.1 and 6.5% in 2020s, 2050s, and 2080s under RCP2.6, 4.5, and 6.0, respectively; however, yield reduction is estimated as −0.7, −3.5 and −10.1% in the respective period under RCP8.5. Sowing of wheat on 10th December in RLR is predicted to increase the yield up to 9.6, 7.8, and 5.0% in the 2020s, 2050s, and 2080s under different scenarios. In CSR, sowing of wheat around 20th December would be more beneficial compared
to other sowing dates as it showed improvement in yield up to 6.5, 5.2, and 4.1% in the 2020s, 2050s, and 2080s under different scenarios. Likewise, in VAR, wheat sowing on 20th December showed maximum yield enhancement up to 9.5, 7.2, and 5.1% in the respective time frames under different RCPs. These results are in good agreement with the previous findings of Attri & Rathore (2003), Jalota et al. (2014) and Bai et al. (2016), in which they revealed that delay in wheat sowing could minimize the adverse effect of climate change.

N-fertilizer rate

Figure 9 illustrates the wheat yield response to the different N-rates (N60, N80, N100, N120, and N140 of RND) under climate change conditions in six ACRs of West Bengal. In all the ACRs, the wheat yield is expected to reduce to a greater extent at a lower nitrogen rate than a higher nitrogen rate. Results showed that in NHR, the wheat yield is expected to decline in future periods under all emission scenarios under nitrogen application at N60, N80, N100, and N120 of RND. In contrast, nitrogen application at N140 resulted in yield enhancement only in the 2020s under RCP2.6. For TTR, simulation results reveal that wheat yield may reduce under all nitrogen rates in different scenarios and future periods. However, the lowest decline in yield is anticipated with N140 of RND in the future. In GAR and CSR, yield decline is expected for all nitrogen levels in the future under RCP2.6, 4.5, 6.0, and 8.5 except in the 2020s with higher nitrogen (N140) application. In RLR and VAR, N120 and N140 of RND show yield improvement under climate change conditions with maximum gain at N140. The maximum increase in yield is expected in RLR in the 2020s (9.3%), 2050s (8.8%), and 2080s (5.3%) under RCP2.6 at N140 of RND. Results thus show that the negative effect of climate change on yield may be alleviated to some extent by higher nitrogen dose adaptation (Ventrella et al. 2012; Bai et al. 2016). It is also notable that yield decline cannot be avoided at the end of the century under possible climate change despite higher nitrogen doses.

Split of N-fertilizer

Yield simulations were performed for wheat using two, three, and four splits of RND under future climate change conditions, and percent change in yield over the six ACRs is shown in Figure 10. In all ACRs, it is observed that nitrogen split adaptation may lessen yield reduction under future climate change conditions. Results revealed that in all ACRs of West Bengal, four RND splits are more beneficial than two or three splits as they showed the most negligible yield reduction under climate change conditions. However, wheat yield is likely to reduce in most of the ACRs despite adopting N-fertilizer splits. An increment of 3.9 and 3.2% in yield is noticed in RLR in the 2020s and 2050s under RCP2.6 with four splits of N-fertilizer. By the end of the century, the highest yield reduction is expected up to −21.2 and −23.24%, respectively, in NHR and TTR despite using four splits of N-rate.

Deficit irrigation scheduling

The effect of deficit irrigations scheduling on wheat yield under climate change conditions was simulated using the CERES model. The percent change in yield is shown in Figure 11. Results reveal that the highest yield decline may reach up to −25.9,
Figure 8 | Percent change in wheat yield with different sowing dates under different scenarios compared to the historical yield over six ACRs; (a) NHR, (b) TTR, (c) GAR, (d) VAR, (e) RLR, (f) CSR.
Figure 9 | Percent change in wheat yield with different N-fertilizer rates under climate change conditions with respect to the historical yield in six ACRs (a) NHR, (b) TTR, (c) GAR, (d) VAR, (e) RLR, (f) CSR.
31.1, and 36.3%, respectively, during the 2020s, 2050s, and 2080s under different RCPs at 60% deficit irrigation scheduling. However, irrigation scheduling at a 20% deficit may enhance yield up to 12.4, 10.7, and 7.1% over different ACRs in the respective future time frames. NHR and TTR showed higher yield reduction than other ACRs when irrigation was scheduled above 40% deficit. RLR showed a higher yield increment than other zones under lesser water-stressed conditions. Results for NHR, TTR, GAR, and VAR showed a minor difference in yield change under climate change conditions when irrigation was

Figure 10 | Percent change in wheat yield with different splits of nitrogen dose in the 2020s, 2050s, and 2080s under different scenarios compared to the historical yield over six ACRs; (a) NHR, (b) TTR, (c) GAR, (d) VAR, (e) RLR, (f) CSR.

31.1, and -36.3%, respectively, during the 2020s, 2050s, and 2080s under different RCPs at 60% deficit irrigation scheduling. However, irrigation scheduling at a 20% deficit may enhance yield up to 12.4, 10.7, and 7.1% over different ACRs in the respective future time frames. NHR and TTR showed higher yield reduction than other ACRs when irrigation was scheduled above 40% deficit. RLR showed a higher yield increment than other zones under lesser water-stressed conditions. Results for NHR, TTR, GAR, and VAR showed a minor difference in yield change under climate change conditions when irrigation was
scheduled at 20, 30, and 40% deficit. It is noticeable that in RLR and CSR, irrigation scheduling at 20 and 30% deficit resulted in almost similar effects on yield under climate change conditions. These results corroborate the findings of Ventrella et al. (2012) and Azad et al. (2018) that irrigation scheduling may attenuate the yield reduction under climate change conditions.
Combined effect of the best-suited adaptation options on wheat

Separate analysis of adaptation options suggests that the most suitable wheat sowing dates are 30th November for TTR and NHR, 20th December for VAR, GAR, and CSR, and 10th December for RLR. In addition, four splits of nitrogen fertilizer at 120% of RND may be recommended in all ACRs. Moreover, irrigation at a 40% deficit of MAW in TTR, NHR, GAR, and VAR and a 30% deficit of MAW in RLR and CSR could be suggested under climate change conditions. The combination of these most appropriate adaptation options was used to simulate wheat yield in different ACRs. Changes in yield under climate change conditions with respect to historical yield were determined to realize the overall adaptation potential to climate change (Table 4). Model simulation results signify a higher possibility of yield improvement in GAR, VAR, and RLR, among other ACRs under climate change conditions. Most of the ACRs show yield increment during the 2020s under RCP2.6, 4.5, 6.0, and 8.5; however, the positive effect of adaptation options on yield decreases with time. Despite adopting the most suitable adaptation options, higher yield reduction is noted in NHR and TTR compared to other ACRs in all time frames under different scenarios. Relatively higher yield improvement is anticipated in VAR in future under different scenarios.

CONCLUSIONS

Feasible adaptation options for rice and wheat crops were evaluated to lessen the detrimental impact of climate change in different ACRs of West Bengal state in Eastern India. Adaptation options, shifting transplanting date, seedling age, and change in rate and number of splits of N-fertilizer are used for rice to simulate yield under projected future climate conditions. In the case of wheat, varying sowing dates, N-fertilizer rate, the different split of N-fertilizer, and deficit irrigation scheduling are used. The calibrated and validated CERES model was utilized for yield simulation of both crops using various adaptation options under different climate change conditions. Simulation results show that CERES can capture the rice and wheat yield over the diverse regions of West Bengal. Moreover, adaptation options analysis implies that the adverse effect of climate change on rice and wheat yield may be smartly reduced by adopting even easily applicable options. However, the potential of different adaptation options to compensate for the negative impact of climate change is location-specific and in this specific study, it varies for different ACRs. The study concludes that in most of the ACRs, postponing transplanting date, 18 days older seedling, N-fertilizer application at 120% of RND at four splits would be favourable for rice yield improvement under climate change conditions. In the case of wheat crop, the combination of delaying sowing date, N-fertilizer application at 120% of RND in four splits, and irrigation at 50 and 40% deficit of MAW may be appropriate adaptation options to offset the negative impact of climate change in most of the ACRs. These findings are based on CMIP5 climate projections, and the effect of new CMIP6 climate projections on the suitability of adaptation options can be further analyzed. This study highlights the role of adaptation options in sustaining/increasing crop yield under future climate change conditions, which is essential for food security. It is suggested that the policymakers should encourage the stakeholder and farming community towards adjusting the existing management practices to cope with the changing climate conditions.

### Table 4 | Percent change in yield (simulated using the most suitable adaptation option) in future climate change conditions compared to the historical yield (simulated using common practice)

|                | NHR | TTR | GAR | VAR | RLR | CSR |
|----------------|-----|-----|-----|-----|-----|-----|
| RCP2.6         |     |     |     |     |     |     |
| 2020s          | 4.5 | 2.3 | 11.7| 15.8| 13.6| 8.3 |
| 2050s          | 1.2 | -4.3| 10.3| 8.8 | 9.3 | 6.5 |
| 2080s          | -6.1|-7.3 | 7.7 | 7.8 | 7.6 | 5.1 |
| RCP4.5         |     |     |     |     |     |     |
| 2020s          | 3.2 | 1.0 | 9.3 | 7.2 | 13.4| 7.8 |
| 2050s          | -6.8| -6.4| 6.3 | 5.6 | 7.2 | 2.9 |
| 2080s          | -8.7| -9.2| 4.8 | 2.4 | 4.6 | 3.3 |
| RCP6.0         |     |     |     |     |     |     |
| 2020s          | -1.2| -6.3| 7.1 | 3.4 | 7.3 | 3.5 |
| 2050s          | -8.1| -8.2| 3.6 | 3.2 | 3.4 | 1.1 |
| 2080s          | -10.1| -10.2| 2.2| -1.1| -4.8| 1.9 |
| RCP8.5         |     |     |     |     |     |     |
| 2020s          | -5.6| -7.1| 2.3 | 2.1 | 3.2 | 3.1 |
| 2050s          | -10.3| -10.2| -1.8| -1.0| 1.1 | -2.1|
| 2080s          | -13.2| -17.0| -8.9| -9.3| -11.3| -10.3|
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Data Availability Statement

All relevant data are included in the paper or its Supplementary Information.

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