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Identifying most promising agronomic adaptation strategies to close rainfed rice yield gap in future: a model-based assessment

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ABSTRACT

There is an increasing consensus that climate change may have a high negative impact on crop yield, and that it will affect farmers in developing and least developed counties the most. 'Closing the yield gap' could be one of the promising options to address the issue of yield improvement. Better understanding of adaptation strategies and implications of the adaptations in crop yield are required to close the yield gap. In this study, the effectiveness of agronomic adaptation options on the rainfed rice yield gap was evaluated for the baseline period (1981–2005) and two future periods (2016–2040 and 2026–2050) for India by using bias-corrected RegCM4 output and the Decision Support System for Agrotechnology Transfer (DSSAT) model. Results suggested that a combined adjustment of transplanting time (advancing by fortnight), crop spacing ((10 × 10) cm) and N-fertilizer application (140 kg/ha) was the best strategy as compared to the single adaptation option to close the yield gap under the climate change scenario. The strategy improved rice yield by 37.5–168.0% and reduced the average attainable yield gap among the cultivars from 0.74 to 0.16 t/ha under future climate projection. This study provides agronomic indications to rice growers and lays the basis for an economic analysis to support policy-makers in charge of promoting the sustainability of the rainfed rice-growing systems.

Key words: agronomic adaptation, climate change, DSSAT, India, yield gap

HIGHLIGHTS

- The study assessed the rice yield gap in India by using the DSSAT model.
- Equidistant quantile mapping technique is used for bias correction of RCM outputs.
- The reduction of yield due to climate change is found to be the lowest for long duration cultivar (~0.25 t/ha).
- Combination of adaptation options improves rice yield by 37.5–168.0%.
- It reduces the average attainable yield gap from 0.74 to 0.16 t/ha among cultivars in future.

1. INTRODUCTION

Ensuring food security is one of the major concerns for developing countries like India, where about 472 million people are undernourished (Rawal *et al.* 2019). Rice crop (*Oryza sativa* L.) plays a major role in global food security as it is a staple food crop for more than half of the world's population. Chauhan & Johnson (2011) suggested that global rice production needs to increase significantly in the coming decades to keep pace with the demands of an increasing population. However, the cultivable area is either fixed or reduced to accommodate the other demands of increasing population and thus restricting any scope of spatial expansion. Consequently, the rice yield must be raised to meet the expected demand. At the same time, it is limited by the increasing number of extreme weather events such as drought and flood because of changing climate (Teixeira *et al.* 2013; Lesk *et al.* 2016).

The projected climate change indicates that the global average surface temperature could increase by up to 4.8 °C and CO_2 concentration could reach up to 550 ppm by the end of 2100, whereas rainfall is likely to vary depending on the latitude (IPCC 2014; Dunne 2018). An increase in temperature shortens the crop phenological phases (flowering and maturity) and affects growth parameters (Teixeira *et al.* 2013), whereas increasing atmospheric CO_2 concentration can directly accelerate crop growth (Godfray *et al.* 2010). Being a C3 crop, rice may gain advantage from increasing CO_2 concentration level in

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photosynthesis, however, it is yet to be revealed whether the overall benefits will outweigh the unfavorable impacts from an increase in temperatures. Past studies (Rosenzweig *et al.* 2001; Barnabás *et al.* 2008) indicate that rice yield could be depressed by hydro-climatic extremes (drought and floods), which are expected to be increased in both frequency and intensity in future due to climate change. To mitigate the impact of the changing climate, it is necessary to understand how rice-growing regions could be affected if plausible climate scenarios are getting unfolded.

In the past, several researchers (Rosenzweig *et al.* 2001; Gregory *et al.* 2005; Schmidhuber & Tubiello 2007; Lobell *et al.* 2008; Mishra *et al.* 2013; Wheeler & Von Braun 2013; Singh *et al.* 2017; Arunrat *et al.* 2018) reported that climate change will influence global rice production in the near future because crop growth is highly sensitive to any alteration in climatic conditions (Dias *et al.* 2016). In the Indian context, the overall change in expected rice yield could vary from 1.2 to 8.8%, 0.7 to 12.6% and −2.9 to 17.8% in the 2020s, 2050s and 2080s, respectively, due to the expected climate change (Gupta & Mishra 2019). The positive percentage change indicates increasing yield, whereas the negative percentage change denotes decreasing yield. The reasons for rice yield decline are reported as an increase in maximum temperature ($T_{\max}$) (Amgain *et al.* 2006) and minimum temperature ($T_{\min}$) (Pathak *et al.* 2003; Amgain *et al.* 2006), decrease in solar radiation (R_s) (Pathak *et al.* 2003; Amgain *et al.* 2006) and change in rainfall (Boonwichai *et al.* 2018).

The assessment of yield gap could be one of the promising options to identify appropriate adaptation strategies which will increase actual yield (Y_a) to ensure food security, as well as reduce the gap from attainable yield (Y_{attain}). Y_{attain}, which is defined as profit maximizing optimum yield under given local economic conditions that takes into account risks and existing constraints (Fischer *et al.* 2009), is considered as a benchmark for the yield gap assessment study. A farmer's yield tends to plateau when it reaches 75–80% of the potential yield due to fertilizer supply trade-off to balance between maximizing benefit and minimizing risk on the entire field scale. Therefore, Y_{attain} is considered as 80% of the potential yield or water limited potential yield (Y_w) in most of the yield gap studies (Laborte *et al.* 2012; van Ittersum *et al.* 2013; Sadras *et al.* 2015; Debnath *et al.* 2018). N-fertilizer is the source of the main nutrient (i.e. nitrogen) which affects crop growth and yield formation; however, at the same time, excessive N-fertilizer has substantial negative environmental effects (Sutton *et al.* 2011). Therefore, effective N-fertilizer management is crucial for optimizing crop yields, maximizing farmers' income and to minimizing negative environmental impacts from reactive N flows. The Y of a particular location depends on climate conditions, crop management practice and type of cultivars. Although climate variables are uncontrollable, crop management practices and selection of cultivars can be managed in order to close the yield gap as well as minimize the negative effect of climate change (Lal *et al.* 2011; Anderson *et al.* 2016; Rajwade *et al.* 2018).

Recently, many studies have been devoted to mitigating the impact of climate change especially due to the increase in temperature on rice phenology by using adaptation strategies like alteration of sowing/transplanting date (Krishnan *et al.* 2007; Mitin 2009; Tripathy *et al.* 2009; Desiraju *et al.* 2010; Babel *et al.* 2011; Mainuddin *et al.* 2013; Dharmarathna *et al.* 2014), irrigation methods (Rajwade *et al.* 2018), nutrient management (Babel *et al.* 2011; Mainuddin *et al.* 2013; Banerjee *et al.* 2016), change in cropping pattern (Weiss 2009), selection of cultivars (Soora *et al.* 2013; Mackill *et al.* 2010; Swain & Thomas 2015) and change in age of seedling (Banerjee *et al.* 2016). However, it is difficult to understand the effect of management practices and climate factors on crop yield by only field observations as it is limited to certain experimental assumptions. For this purpose, crop yield simulation models can serve to better understand 'if-then-what' conditions under different crop input management and climate scenarios (Debnath *et al.* 2018). In the past, many researchers have used the Decision Support System for Agrotechnology Transfer (DSSAT) model for climate change adaptation studies (Satapathy *et al.* 2014; Rajwade *et al.* 2018; Boonwichai *et al.* 2019). It is seen that most of the climate change adaptation studies did not attempt to consider yield gap assessment which could provide a maximum possible range of yield improvement by using adaptation options. On the other hand, past studies on both climate change adaptation and yield gap are mostly concentrated on location-specific applications (Tripathy *et al.* 2009; Mishra *et al.* 2013; Swain & Thomas 2015; Banerjee *et al.* 2016; Singh *et al.* 2016) which constrain to reproduce the effect of different localized alterations of weather variables and soil properties on crop yield. Hence, the implementation of spatially distributed fine resolution weather and soil information may result in improved accuracy in the regional study. Therefore, for the evaluation of adaptation options on rice yield it is crucial to consider yield gap, fine resolution weather and soil information to understand the magnitudes of rice yield that could be improved against the changing climate. The objective of the study was to evaluate the effectiveness of adaptation strategies including change in transplanting date, N-fertilizer application level, crop spacing and cultivar type for improving the rice yield vis-a-vis reducing the yield gap under expected future climatic projection in India by using the DSSAT model.

2. MATERIALS AND METHODS

2.1. Study area

Rice is one of the dominant food crops in India which is cultivated in 43 Mha (~30% of total cultivable land) by using different methods based on farming type (irrigated, rainfed and deepwater), crop management (single crop and multi-crop) and seasons (Kharif and Rabi) of the region. The Kharif season (starts in June and ends in October) contributes more than 85% of the total rice production in the country. The official survey data from the Ministry of Agriculture and Farmers Welfare, Govt. of India for the period 1986–2015 were used to identify major rice-growing states in the country. The 30-year mean yields and the total rice productions for each state were calculated and categorized. The selection of major rice-growing states, in the present study, is based on either average annual rice production (total rice production of the state greater than 2 Mt) or share of rice area (having share of the rice planting area greater than 50% of the total food grains area of the state). Based on these criteria, 17 major rice-growing states have been selected as the study area (Figure 1). The yield attributes of selected states are presented in Table 1.

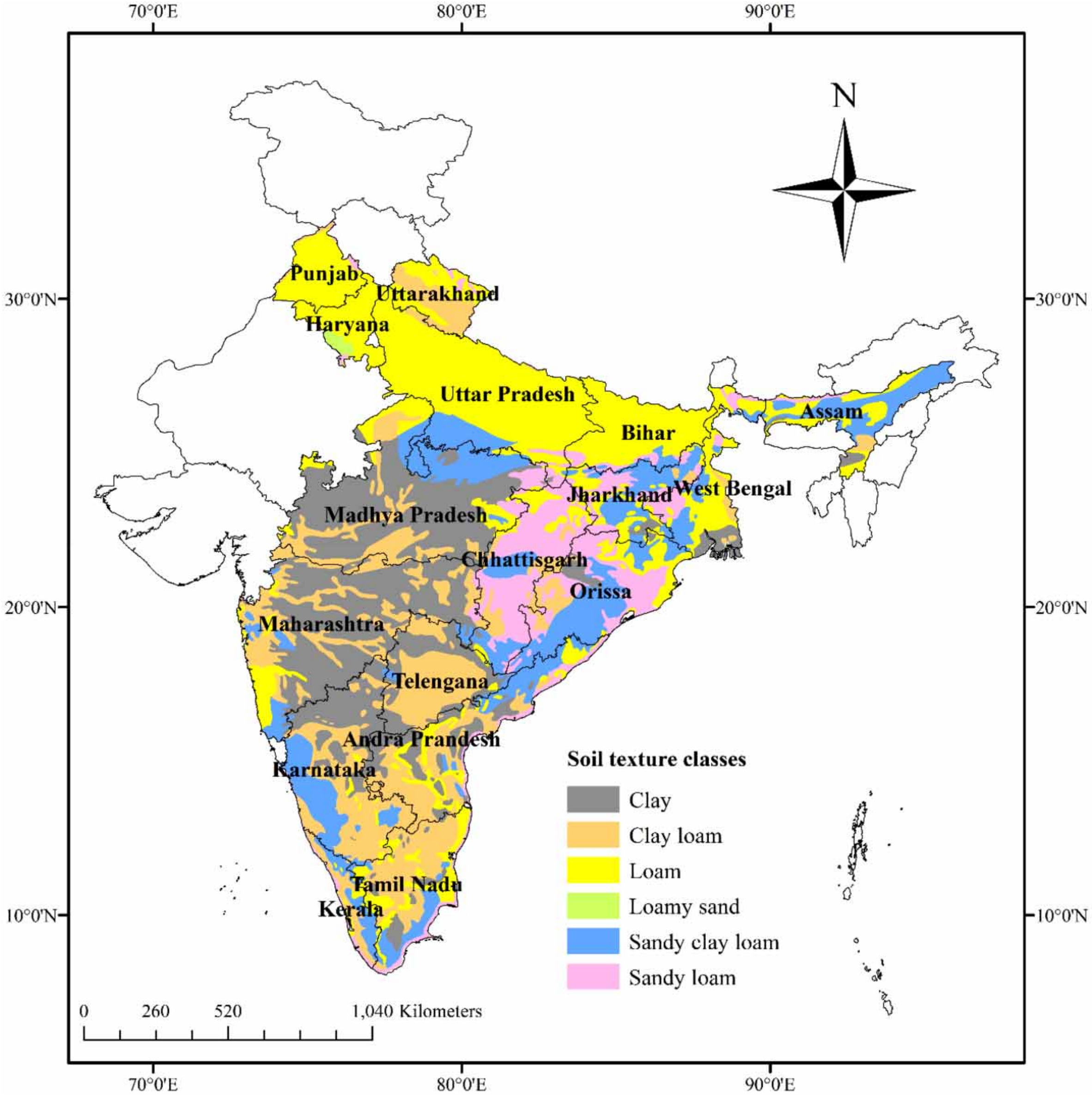

Figure 1 | Index map of the study area showing the selected major rice-growing states and soil types.

Table 1 | Observed kharif season rice yield information of the major rice-growing states of India during 2017–2018 (source: Ministry of Agriculture and Farmers Welfare, Govt. of India)

State	Total food grain area (Mha)	Rice cultivated area (Mha)	Share of rice cultivated area (%)	Rice production (Mt)	Mean rice yield (t/ha)
Andhra Pradesh (AP)	2.09	1.48	70.67	4.94	3.35
Assam (AS)	2.08	2.03	97.74	4.09	2.01
Bihar (BR)	3.52	3.24	92.02	7.95	2.45
Chhattisgarh (CH)	4.20	3.76	89.55	4.93	1.31
Haryana (HR)	1.95	1.42	72.92	4.52	3.18
Jharkhand (JH)	2.45	1.74	70.82	4.08	2.35
Karnataka (KT)	4.66	0.74	15.82	2.23	3.03
Kerala (KR)	0.15	0.15	96.67	0.39	2.67
Madhya Pradesh (MP)	6.75	2.02	29.97	4.10	2.02
Maharashtra (MH)	5.71	1.43	24.96	2.67	1.87
Odisha (OD)	4.11	3.54	86.23	5.86	1.65
Punjab (PN)	3.19	3.07	96.08	13.38	4.37
Tamil Nadu (TN)	2.48	1.67	67.38	5.92	3.54
Telangana (TG)	2.02	1.05	51.83	2.95	2.81
Uttar Pradesh (UP)	8.45	5.79	68.50	13.20	2.28
Uttarakhand (UK)	0.47	0.24	50.85	0.61	2.53
West Bengal (WB)	4.00	3.86	96.45	10.69	2.77
India (including other states)	72.00	39.35	54.65	97.14	2.47

2.2. Climate change scenarios

Regional climate models (RCMs) have been increasingly used in recent decades to generate climate information on a finer scale than those of global climate models (GCMs) across regions around the world. There are three RCMs, namely HadGEM3-RA, RegCM4 and YSU_RSM, which have consistency in data availability without any missing information and cover India in its entirety. The RCMs simulated outputs are available with two representative concentration pathways (RCPs) scenarios (RCP 4.5 and RCP 8.5) at $0.44 \times 0.44°$ spatial resolution for the period of 1981–2050. Debnath *et al.* (2021) found that the RCP 8.5 scenario of the RegCM4 model performed well to simulate rice yield than other models in the study area under future climatic conditions. Therefore, the output of the RCP 8.5 scenario of the RegCM4 model was chosen in the present study for evaluating the effectiveness of adaptation on rice yield and yield gap under expected future climatic projection. It is the latest version of the RegCM model with some noteworthy improvements, namely the coupling of a sophisticated land surface model (LSM) and Community Land Model, version 3, developed by the International Centre for Theoretical Physics (ICTP) (Suh *et al.* 2012). The RCM downscaled the global simulations from Atmosphere-Ocean coupled Hadley Center Global Environmental Model version 2 (HadGEM2-AO) over the Coordinated Regional Climate Downscaling Experiment (CORDEX) domain for East Asia. In HadGEM2-AO, processes included are troposphere, land surface and hydrology, aerosols and ocean and sea-ice (Bellouin *et al.* 2011). In this study, daily climate simulation datasets ($T_{\max}$, $T_{\min}$, R_s and rainfall) of the RCM were downloaded from the CORDEX East Asia website (http://cordex-ea.climate.go.kr/cordex/) for the period of 1981–2050 and extracted for the study area. Climate scenarios were considered in the study for the period 2016–2040 (2030s) and 2026–2050 (2040s). The observed 25 years (1981–2005) gridded ($0.25° \times 0.25°$) $T_{\max}$, $T_{\min}$ and rainfall from the India Meteorological Department (IMD) along with R_s from the National Centers for Environmental Prediction (NCEP) at $0.3° \times 0.3°$ resolution were taken as the baseline data for the study area.

2.3. Climate data processing

A limited understanding of the atmosphere and simplified representation of its process in RCM simulation led to bias in its output. Therefore, the errors in the seasonal cycle of climate simulation datasets of the above-mentioned RCMs are bias corrected on a monthly scale by using equidistant quantile mapping (EDQM) (Li *et al.* 2010; Sachindra *et al.* 2014). Before bias correction, the raw datasets are rescaled to 0.25° × 0.25° resolution by using the bilinear interpolation method. In the EDQM technique, initially, the empirical cumulative distribution functions (CDFs) for the observed weather output and RCMs' weather output were derived for the baseline period. Then the empirical CDF was developed for the weather output of RCM under future climate scenario. In the next step, the bias-corrected RCM output of the baseline period was calculated by mapping CDF of the RCM output of the baseline period onto the CDF of the observed weather output. For the bias-corrected RCM output under the future climate scenario, the value calculated from the previous step was added with the climate shifting factor which takes into account the changes in variability between baseline and future RCM output simulations. More details about bias correction of climate variables by using the EDQM technique are reported by Sachindra *et al.* (2014).

2.4. Crop simulation model

The DSSAT version 4.5 (Jones *et al.* 2003; Hoogenboom *et al.* 2009) crop growth simulation model was used to simulate future rice yield under climate change scenarios in this study. The model simulates crop growth and yield as a function of the soil–plant–atmosphere dynamics by taking into account weather, soil characteristics, crop management practice and genetic coefficients of the cultivar. The genetic coefficients of a cultivar are mainly based on photoperiod sensitivity, grain filling duration, gain weight, temperature tolerance, etc. The required model inputs include daily weather data ($T_{\max}$, $T_{\min}$, R_s, rainfall), soil data (soil texture, permanent wilting point, field capacity, saturation moisture content), cultivar information (i.e. cultivar's genotype coefficients) and rice experiment data (timing of sowing/transplanting, irrigation, fertilizer application and harvesting). The model is used worldwide for different crop growth simulations such as rice, wheat and maize for assessing the potential impact of climate change on crop production (Mishra *et al.* 2013; Swain & Thomas 2015; Gupta & Mishra 2019) and adaptation analysis (Babel *et al.* 2011; Mishra *et al.* 2013; Dharmarathna *et al.* 2014; Swain & Thomas 2015; Rajwade *et al.* 2018).

In this study, the DSSAT model was used to simulate water limited potential yield (Y_w) and actual yield (Y_a) dynamically in all grid points covering the study area for the baseline, 2030 and 2040s period with the help of an open-source database software (MySQL version 6.1) and high-level programming language-Python (Python version 3.4.3). Databases for weather and soil information are prepared to store the input information of each grid in MySQL. A python programming code was used to retrieve grid wise weather and soil information from the database and the DSSAT compatible input file formats were prepared (.WTH and .SOL). In addition to these, the Python code also writes the crop management file (.SNX) and finally runs the model by linking all these three files. The same procedure was followed for all grids one-by-one for a given period. The output files of the model (.OSU, .OOV and warning.OUT) were arranged grid wise for further analysis. The flowchart of the various steps involved in the dynamic simulation of the model is shown in Figure 2.

2.5. Evaluation of agronomic adaptation options

As agronomic adaptation options, seven transplanting dates starting on 1st June up to 31st August at fortnight interval, six levels of N-fertilizer (40, 80, 100, 120, 140, 160 kg/ha) and five different crop spacings ((10 × 10) cm, (15 × 15) cm, (20 × 20) cm, (25 × 25) cm and (30 × 30) cm) along with three different cultivars, namely short duration (Shankar and Saket-4), medium duration (NDR-359 and IR36) and long duration cultivars (Swarna and PR 106) are considered in this study for the identification of effective adaptation options for future. Generally, short duration, medium duration and long duration cultivars take 100–120 days, 120–140 days and more than 160 days, respectively, to mature from sowing time (Rice Knowledge Bank 2020). Mishra *et al.* (2013) reported that the transplanting dates for rice crop generally vary from 15th June to 20th July in the study region depending on the onset of monsoon. Therefore, for change in the transplanting date strategy, the 15th June, 1st July and 15th July are considered to represent baseline transplanting dates for long duration, medium duration and short duration, respectively, in the study area. Crop spacing of (20 × 20) cm, N-fertilizer level of 120 kg/ha and transplanting date of 15th June, 1st July and 15th July, respectively, were considered as current recommended practice (i.e. baseline condition) for long, medium and short duration cultivars in the study. The DSSAT model simulates Y_w and Y_a of Shankar and IR36 rice cultivars by using calibrated values from field observations at research plots of the Agricultural and Food Engineering Department (AgFE) during 2015–2017 (Debnath *et al.* 2018), whereas the model simulates for remaining cultivars in

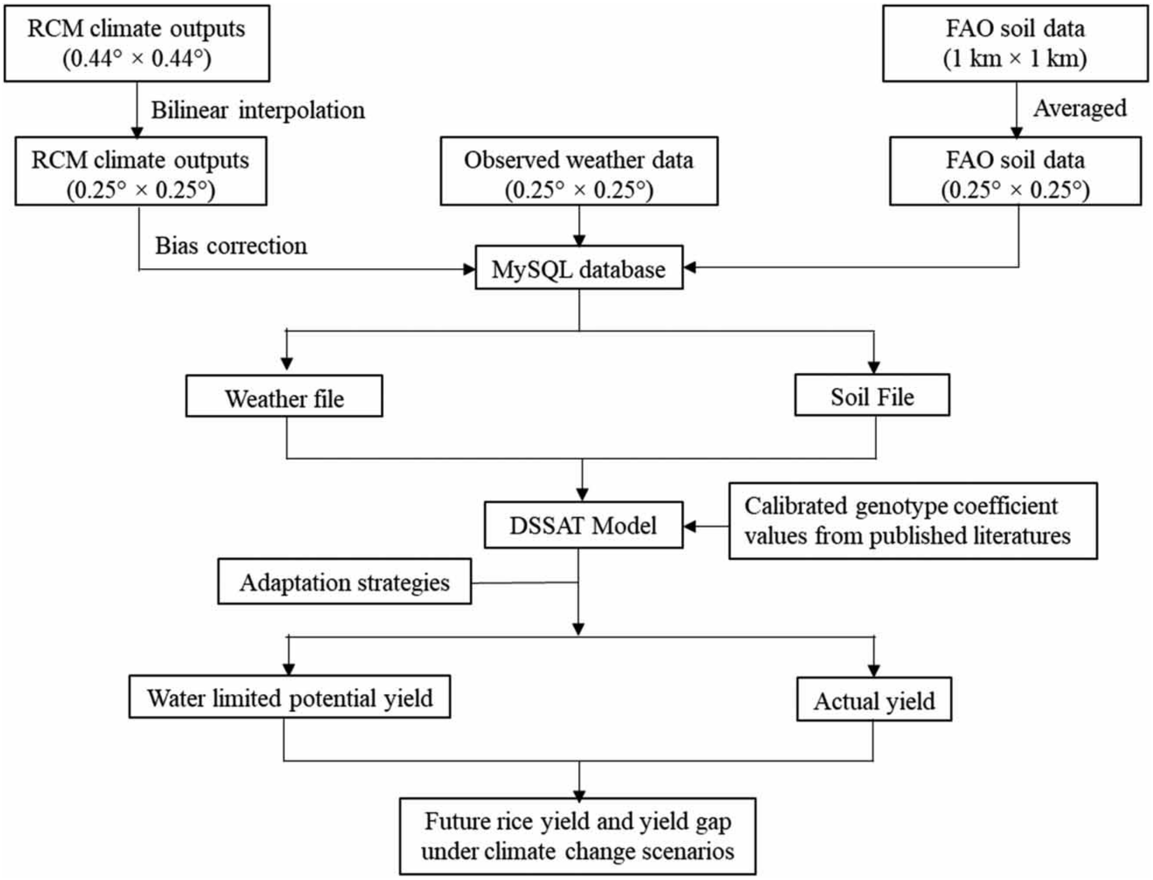

Figure 2 | Flowchart to identify best adaptation strategies by using RCMs projection and the DSSAT model.

the study area by using calibrated genotype coefficient values from published literature (Pathak *et al.* 2003; Kumar & Tripathi 2011; Satapathy *et al.* 2014). The in-built software of DSSAT, Genotype Coefficient Calculator (GENCALC), was used to identify genotype coefficients of the cultivars (Hunt *et al.* 1993). The model performance was evaluated by comparing observed and model simulated growth and yield attributes by visual interpretation as well as by using three statistical performance indices: RMSE$_n$, R^2 and D-index. The effectiveness of adaptation options is evaluated based on the percentage change in yield and yield gap.

2.5.1. Percentage change in yield

The change in rice yield of each cultivar with respect to the adaptation option is calculated as follows:

$$Y_{\mathrm{d},i} = \frac{Y_{\mathrm{a},i} - Y_{\mathrm{f}}}{Y_{\mathrm{f}}} \times 100 \tag{1}$$

where $Y_{\mathrm{a},i}$ is the actual yield with respect to adaptation option i (t/ha), Y_{f} is the actual yield with respect to current recommended practice (t/ha), $Y_{\mathrm{d},i}$ is the change in yield (%) with respect to adaptation option i.

2.5.2. Estimation of yield gap

The rice yield gap of each cultivar with respect to the adaptation option is calculated as follows:

$$\Delta Y_{\mathrm{attain},i} = (Y_{\mathrm{attain}} - Y_{\mathrm{a},i}) \tag{2}$$

$$= 0.8 \times Y_{\mathrm{w}} - Y_{\mathrm{a},i} \tag{3}$$

where $\Delta Y_{\text{attain},i}$ is the attainable yield gap of the cultivar (t/ha), Y_{attain} is the attainable yield of cultivar (t/ha), $Y_{\text{a},i}$ is the actual yield with respect to adaptation option i (t/ha) and Y_{w} is the water limited potential yield of cultivar (t/ha).

3. RESULTS AND DISCUSSION

3.1. Investigation on climate change response

The gridded observed weather data of the baseline period (1981–2005) and future weather data of the RegCM4 model under the RCP 8.5 scenario in two time slices, 2030s and 2040s, were analyzed to investigate climate change response in each major rice-growing state of India. Figure 3 shows monthly mean of $T_{\max}$, $T_{\min}$ and R_{s}, and mean annual rainfall of the study area for the baseline period. The monthly mean $T_{\max}$ varied from 23.8 to 34.4 °C during the baseline period, which is expected to be increased by 0.61 to 2.30 °C (average 1.27 °C) and 0.98 to 2.78 °C (average 1.71 °C) in the 2030s and 2040s, respectively. The monthly mean $T_{\min}$ ranged from 12.4 to 24.5 °C in the baseline period. Similar to $T_{\max}$, $T_{\min}$ is also expected to increase throughout the study area with an average of 1.35 °C and 1.75 °C during two future periods (2030s and 2040s, respectively). Among all the states, maximum increment in both $T_{\max}$ and $T_{\min}$ is expected to occur in Uttarakhand and Punjab during the 2030s and 2040s, respectively, whereas minimum values may be observed in Assam during the 2030s. Unlike $T_{\max}$ and $T_{\min}$, the monthly mean R_{s} in the study area is expected to be decreased with an average of −0.63 and −0.66 MJ/m^2 day in the future. The mean annual rainfall may increase by 170.15 cm in 2030s, however, it is likely to be decreased in the 2040s as compared to the 2030s in the study area. The maximum rainfall increase is expected in Kerala (during 2030s) and Assam (2040s), whereas it may be minimum in Haryana (during 2030s) and Madhya Pradesh (during 2040s).

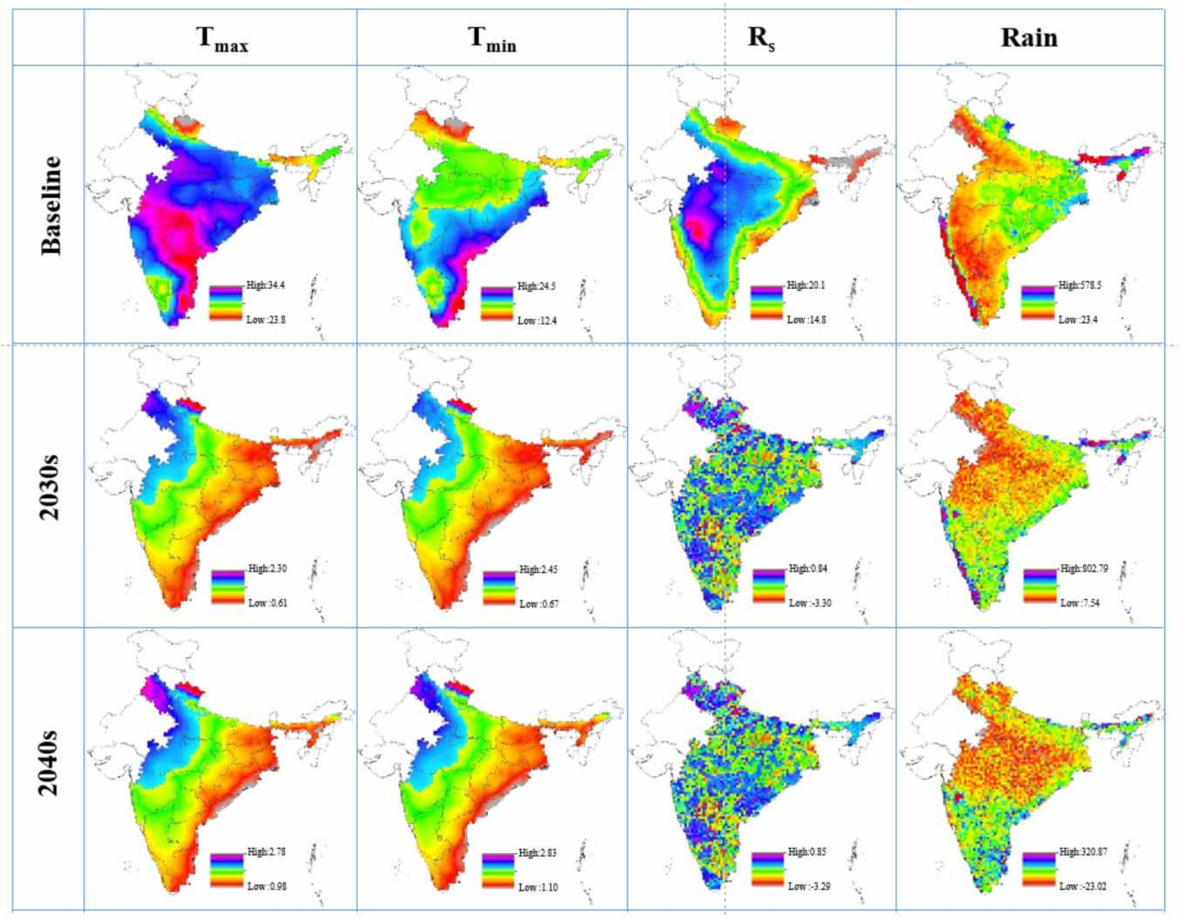

Figure 3 | Variation of monthly mean of $T_{\max}$, $T_{\min}$ and R_{s}, and mean annual rainfall in the baseline period as well as climate change in future.

3.2. DSSAT model performance

The DSSAT model was calibrated and validated using the field experimental data collected during 2015–2016 and 2016–2017, respectively, for both Shankar and IR36 cultivars. The RMSE$_n$, R^2 and D-index values of model performance are found to be 14.3%, 0.90 and 0.98, respectively, for Shankar, whereas 17.9%, 0.87 and 0.97, respectively, for the IR36 cultivar. The performance indices showed a good agreement between observed and simulated grain yield at the experimental site (Figure 4). The coefficient of determination (R^2) statistics of the model performance during the validation period are found to be 0.68 and 0.64 for Shankar and IR36, respectively, though D-index for grain yield is >0.75 (acceptable model fit suggested by Yang *et al.* 2014).

It could be noted that the major rice-growing states of India consist of a large spatial variation of soil properties and climate characteristics, which makes the DSSAT model calibration quite difficult for every part of the study area. Moreover, the main aim of this study was not to evaluate the model capability as the model has been successfully used in many places of India where researchers have shown its usefulness for simulating rice yield (Pathak *et al.* 2003; Shukla & Matthews 2004; Kumar & Tripathi 2011; Mishra *et al.* 2013; Satapathy *et al.* 2014; Rajwade *et al.* 2018; Debnath *et al.* 2018). Gupta & Mishra (2019) compared average yield simulated from observed and multi-GCM ensemble of historical yield for the period 1976–2005 at 20 agroecological zones in India by using calibrated genotype coefficients values from Satapathy *et al.* (2014) to examine the appropriateness of the model. The results justified the model's capability to simulate rice yield at the regional scale quite reasonably (Pearson's correlation for all agroecological zones was varied from 0.89 to 0.99) while using well-calibrated coefficients values of any particular location with appropriateness. Therefore, calibrated coefficients of Shankar and IR36 found by using field observation at AgFE along with calibrated genotype coefficient values from different published literatures (Saket-4 (Shukla & Matthews 2004), NDR-359 (Kumar & Tripathi 2011), Swarna (Satapathy *et al.* 2014) and PR106 cultivar (Pathak *et al.* 2003)) are used to simulate Y_w and Y_a throughout the study area.

3.3. Climate change impact on rice yield and yield gap

The DSSAT model was used to simulate Y_w and Y_a of all six cultivars in each grid of the study area by using observed weather information from IMD for the baseline period as well as weather outputs of the RegCM4 model under the RCP 8.5 scenario. By assuming the same field management practices in the future, making climate the only variable, the impact of projected climate change on rice yield and yield gap is assessed by comparing Y_w and Y_a in the study. The model simulates Y_w and Y_a by considering the currently recommended crop spacing of 20 cm × 20 cm and N-fertilizer level of 120 kg/ha (Mishra *et al.* 2013; Debnath *et al.* 2018; Debnath *et al.* 2021; Rice Knowldege Bank 2021) under timely transplanting date (i.e. 15th June to 15th July) conditions (Mishra *et al.* 2013). Table 2 shows variation of Y_w and Y_a with respect to cultivars during the baseline period as well as in the future. The model predicted the mean Y_w varied from 3.67 to 6.82 t/ha with an average of 5.13 t/ha during the baseline period, whereas the mean Y_a varied from 1.89 to 4.64 t/ha with an average of 3.32 t/ha in the study area. As a result, the ΔY_{attain} varied from 0.42 to 1.05 t/ha with an average of 0.78 t/ha in the study area. The model simulation results indicated that both Y_w and Y_a may be maximum for the long duration cultivar, whereas

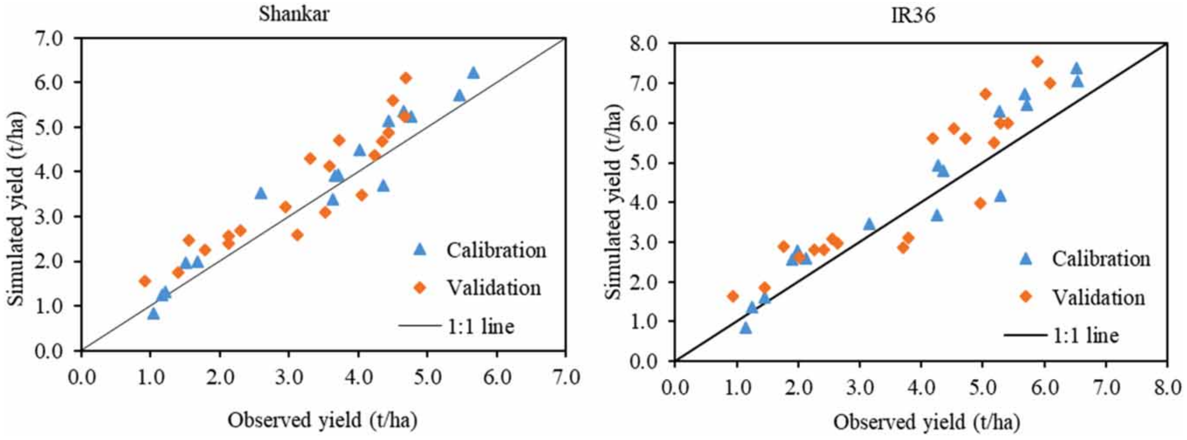

Figure 4 | Comparison between observed and simulated rainfed rice yield at a research plot of AgFE.

Table 2 | Impact of climate change on rice yield and yield gap by using the current recommended management practice in India

	Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)		
		RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
Saket-4	3.82	3.40	3.35	2.11	1.55	1.51	0.95	1.17	1.17
Shankar	3.67	3.08	3.01	1.89	1.39	1.34	1.05	1.07	1.07
IR36	5.31	4.97	4.77	3.71	3.26	3.21	0.54	0.72	0.61
NDR-359	4.75	4.30	4.22	3.38	2.94	2.90	0.42	0.50	0.48
Swarna	6.82	6.10	5.91	4.64	4.40	4.35	0.82	0.48	0.38
PR106	6.43	5.75	5.65	4.21	3.99	3.95	0.93	0.61	0.57

the same may be minimum for short duration cultivars. The maximum rice yield may be produced in the state of Punjab for all rice cultivars, whereas the highest yield gap may be experienced in Chhattisgarh during the baseline period. Due to the expected climate change in the future, the mean Y_w is likely to decrease from 5.13 t/ha (baseline period) to 4.60 and 4.49 t/ha during the 2030s and 2040s, respectively. Similar to Y_w, the mean Y_a of the study area is also likely to decrease from 3.32 t/ha (baseline period) to 2.92 and 2.88 t/ha during the 2030s and 2040s, respectively. This could be attributed to the increase in temperature, which leads to higher evaporation and transpiration rates as well as future crop water requirements. The modeling based analysis showed that the mean ΔY_{attain} of the study area may remain almost the same in the future.

3.4. Effect of adaptation options on rice yield and yield gap

Based on the model results reported above, the rice yields are expected to be reduced in the future under climate change conditions without adaptation strategies. To mitigate the effects of climate change on rice yield, four adaptation strategies, i.e. change in transplanting timing, crop spacing, N-fertilizer application rate and selection of cultivars were considered.

3.4.1. Change in transplanting date

The DSSAT model was used to simulate rice yield by shifting the transplanting date from 1st June to 31st August for three types of rice cultivars (short duration: Saket-4, Shankar; medium duration: IR36, NDR-359; long duration: Swarna, PR106) in the major rice-growing states of India under the RCP 8.5 climate change scenario. Table 3 shows attainable yield gap (ΔY_{attain}) and percentage change in yield (Y_d) of each change in the transplanting date strategy with respect to the baseline average rainfed yield for the baseline period (1981–2005) as well as future periods (2030 and 2040s). The results showed that advancing the transplanting date could increase rice yield irrespective of the type of cultivar under both the baseline period and RCP 8.5 scenario in the study area. For the short duration cultivar, advancing the transplanting date by a fortnight (i.e. 1st July) from the baseline (i.e. 15th July) would cause an increase in yield of 26.1% (Saket-4) and 28.1% (Shankar) in the base period, which could extend up to 52.9–55.3% in the future period. At the same time, average ΔY_{attain} of the short duration cultivar could be reduced from 1.00 to 0.71 t/ha, 1.12 to 0.46 t/ha and 1.12 to 0.47 t/ha in the baseline period, 2030s and 2040s, respectively. Similar to the short duration cultivar, advancing the transplanting date by fortnight from the baseline condition may increase rice yield of medium and long duration cultivars, respectively, by 6.4–8.7%, 6.8–8.8% in the baseline period to 13.8–16.4%, 8.9–11.3% in future. The average ΔY_{attain} of the long duration cultivar was also reduced for the base period as well as for future years. However, the opposite pattern of average ΔY_{attain} was observed for the medium duration cultivar for the baseline period. Dharmarathna *et al.* (2014) also concluded that seasonally averaged rice yield would increase compared to the base condition when the planting date is advanced by 1 month (i.e. to June). It is well known that increasing temperature due to climate change is expected to result in declining rice yields in the tropics (Pathak *et al.* 2003; Krishnan *et al.* 2007; Mackill *et al.* 2010). In addition to the direct effect of high temperature in reducing yields, extreme weather events will also result in reduced yields and increase the risks of rice farming. The abiotic stresses are expected to worsen as the consequences of climate change including the stresses from high temperatures, drought, flooding and salinity. The quantity of rainfall available to the crop during growing season and the timing of dry spells at sensitive crop growth stages depends on the transplanting timing of the crop. The decline in yield was lower in advanced transplanting as compared to

Table 3 | Variation of rice yield with respect to different transplanting dates under recommended crop spacing (20 cm × 20 cm) and N-fertilizer level (120 kg/ha) in the baseline period and RCP8.5 scenario of 2030 and 2040s

			Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)			Y_d (%)		
				RCP 8.5			RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**Adaptation strategies**	**Date**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
Saket-4	Advancing by 1.5 month	1st Jun	4.52	3.72	3.56	2.91	2.65	2.55	0.71	0.33	0.30	37.9	71.0	68.9
	Advancing by 1 month	15th Jun	4.46	3.77	3.67	2.77	2.53	2.46	0.80	0.49	0.48	31.2	63.1	62.8
	Advancing by fortnight	1st Jul	4.20	3.61	3.53	2.66	2.39	2.31	0.70	0.50	0.52	26.1	53.9	52.9
	Delayed by fortnight	1st Aug	3.22	2.99	2.94	1.95	1.32	1.29	0.63	1.07	1.06	−7.6	−14.8	−14.6
	Delayed by 1 month	15th Aug	2.75	2.66	2.60	1.66	1.17	1.14	0.54	0.96	0.94	−21.3	−24.5	−24.5
	Delayed by 1.5 months	31st Aug	2.36	2.35	2.33	1.33	1.02	0.97	0.56	0.86	0.89	−37.0	−34.2	−35.8
	Baseline transplanting date	15th Jul	3.82	3.40	3.35	2.11	1.55	1.51	0.95	1.17	1.17			
Shankar	Advancing by 1.5 month	1st Jun	4.11	3.26	3.09	2.73	2.48	2.41	0.56	0.13	0.06	44.3	78.2	79.7
	Advancing by 1 month	15th Jun	4.09	3.30	3.17	2.67	2.42	2.35	0.61	0.22	0.19	41.1	73.9	75.1
	Advancing by fortnight	1st Jul	3.91	3.22	3.12	2.42	2.16	2.08	0.71	0.42	0.42	28.1	55.2	55.3
	Delayed by fortnight	1st Aug	3.20	2.80	2.73	1.73	1.34	1.28	0.83	0.90	0.90	−8.5	−3.6	−4.5
	Delayed by 1 month	15th Aug	2.74	2.45	2.39	1.48	1.18	1.15	0.71	0.78	0.76	−21.7	−15.1	−14.2
	Delayed by 1.5 months	31st Aug	2.33	2.24	2.14	1.20	1.01	0.96	0.66	0.78	0.75	−36.5	−27.3	−28.4
	Baseline transplanting date	15th Jul	3.67	3.08	3.01	1.89	1.39	1.34	1.05	1.07	1.07			
IR36	Advancing by 1 month	1st Jun	5.89	5.03	4.62	4.09	3.85	3.78	0.62	0.17	−0.08	10.2	18.1	17.8
	Advancing by fortnight	15th Jun	6.06	5.40	5.13	4.03	3.79	3.74	0.81	0.53	0.37	8.7	16.3	16.4
	Delayed by fortnight	15th Jul	5.30	5.16	5.04	3.54	2.96	2.88	0.70	1.17	1.15	−4.6	−9.2	−10.3
	Delayed by 1 month	1st Aug	4.37	4.33	4.19	3.25	2.81	2.67	0.25	0.65	0.68	−12.4	−13.8	−16.8
	Delayed by 1.5 month	15th Aug	3.57	3.68	3.52	2.66	2.54	2.43	0.20	0.40	0.39	−28.3	−22.1	−24.3
	Delayed by 2 months	31st Aug	2.87	3.13	2.97	2.16	2.14	2.11	0.14	0.36	0.27	−41.8	−34.4	−34.3
	Baseline transplanting date	1st Jul	5.31	4.97	4.77	3.71	3.26	3.21	0.54	0.72	0.61			
NDR-359	Advancing by 1 month	1st Jun	5.49	4.70	4.59	3.80	3.56	3.54	0.59	0.20	0.13	12.4	21.1	22.1
	Advancing by fortnight	15th Jun	5.28	4.62	4.54	3.60	3.34	3.30	0.63	0.35	0.33	6.4	13.8	13.8
	Delayed by fortnight	15th Jul	4.17	3.93	3.85	2.97	2.44	2.35	0.37	0.70	0.73	−12.1	−17.0	−19.0
	Delayed by 1 month	1st Aug	3.51	3.43	3.36	2.61	2.15	2.08	0.20	0.59	0.61	−22.8	−26.9	−28.3
	Delayed by 1.5 month	15th Aug	3.08	3.08	2.98	2.32	2.31	2.26	0.14	0.15	0.12	−31.4	−21.4	−22.1
	Delayed by 2 months	31st Aug	2.81	2.81	2.69	2.05	1.93	1.86	0.20	0.32	0.29	−39.3	−34.4	−35.9
	Baseline transplanting date	1st Jul	4.75	4.30	4.22	3.38	2.94	2.90	0.42	0.50	0.48			
Swarna	Advancing by fortnight	1st Jun	7.16	6.49	6.32	4.96	4.79	4.77	0.77	0.40	0.29	6.8	8.9	9.6
	Delayed by fortnight	1st Jul	6.37	5.87	5.67	4.42	4.08	4.05	0.68	0.62	0.49	−4.7	−7.3	−6.9
	Delayed by 1 month	15th Jul	5.63	5.38	5.22	4.15	3.87	3.84	0.35	0.43	0.34	−10.6	−12.0	−11.7
	Delayed by 1.5 month	1st Aug	4.55	4.56	4.43	3.46	3.26	3.22	0.18	0.39	0.32	−25.4	−25.9	−26.0
	Delayed by 2 months	15th Aug	3.79	3.69	3.64	2.88	2.69	2.64	0.15	0.26	0.27	−37.9	−38.9	−39.3
	Delayed by 2.5 months	31st Aug	3.29	3.12	3.11	2.48	2.29	2.25	0.15	0.21	0.24	−46.6	−48.0	−48.3
	Baseline transplanting date	15th Jun	6.82	6.10	5.91	4.64	4.40	4.35	0.82	0.48	0.38			
PR106	Advancing by fortnight	1st Jun	6.85	6.11	5.95	4.58	4.43	4.40	0.90	0.46	0.36	8.8	11.0	11.3
	Delayed by fortnight	1st Jul	5.90	5.44	5.31	3.97	3.64	3.61	0.75	0.71	0.64	−5.7	−8.8	−8.6

(*Continued.*)

Table 3 | Continued

			Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)			Y_d (%)		
				RCP 8.5			RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**Adaptation strategies**	**Date**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
	Delayed by 1 month	15th Jul	5.47	5.23	5.12	3.72	3.45	3.42	0.66	0.73	0.68	−11.6	−13.5	−13.4
	Delayed by 1.5 month	1st Aug	4.25	4.26	4.13	3.27	3.09	3.04	0.13	0.32	0.26	−22.3	−22.6	−23.0
	Delayed by 2 months	15th Aug	3.65	3.55	3.39	2.75	2.58	2.52	0.17	0.26	0.19	−34.7	−35.3	−36.2
	Delayed by 2.5 months	31st Aug	3.08	2.92	2.74	2.32	2.15	2.10	0.14	0.19	0.09	−44.9	−46.1	−46.8
	Baseline transplanting date	15th Jun	6.43	5.75	5.65	4.21	3.99	3.95	0.93	0.61	0.57			

delayed transplanting. The highest amount of rainfall is utilized when 1st June is planned as the transplanting date, whereas with the delayed transplanting date (31st August) the amount of rainfall received during the crop growing period is found to be the lowest. The delayed transplanting had maximum grain yield reduction in the future climate scenario at all the grids covering the study area. The yield of the long duration cultivar was higher than medium and short duration cultivars for all study periods. The findings of this analysis are supported by Krishnan *et al.* (2007) and Rajwade *et al.* (2018), who stated that high daily average temperature (>35 °C) during the flowering period throughout the area was the main reason for rice yield reduction. Moreover, with delayed transplanting, the rice crop receives a lower amount of rainfall as compared to early transplanting across the locations in the future climate scenario that causes grain yield reduction as the rice is grown under the rainfed ecosystem. Therefore, an adjustment in transplanting timing could be implemented at the field level to reduce the detrimental effect on rice production.

3.4.2. Change in crop spacing

Table 4 shows the response of rice yield with respect to five crop spacings considered in the study. The model simulation results showed that reducing crop spacing from the baseline (i.e. (20 × 20) cm) could increase rice yield and vice versa. The highest yield was found for (10 × 10) cm spacing for all the three types of cultivars, whereas the lowest yield was estimated at (30 × 30) cm. The results revealed that changing crop spacing to (10 × 10) cm could increase the crop yield by 48.3–57.5%, 10.3–13.3% and 8.4–11.8% for short, medium and long duration cultivars, respectively, in the future. At the same time, the average ΔY_{attain} of all cultivars may increase from 0.73 to 1.25 t/ha in the study area which suggested the scope for more yield improvement by considering other agronomic options.

Gunri *et al.* (2004) examined the effect of different crop spacings on rice yield by using field trials and found that closer row spacing (15 × 15) cm produced better rice yield, nitrogen-use efficiency and nitrogen uptake than the wider row spacing (20 × 15) cm. Chauhan & Johnson (2011) found that rice plant densities were not affected by the crop row spacing, however, yields in the 15-cm row spacing condition were 26 and 32% greater as compared to 30-cm row spacing in the dry season and wet season, respectively. Mohaddesi *et al.* (2011) reported that rice crop grown with wider spacing allowed it to draw nutrients from a greater surrounding area and gets more solar radiation to absorb for better photosynthesis and hence performed better as individual plant, though yield may deviate from this linearity due to a smaller number of plants grown per unit area. Chauhan & Johnson (2011) reported that rice yield in wider spacing could be vulnerable to weed competition for the longest period. Alam *et al.* (2012) found that closest spacing produces the shortest plant and a smaller number of tillers per hill might be due to more competition for nutrients, moisture, space and light among the plants in closest spacing.

3.4.3. Change in N-fertilizer application

The DSSAT model was used to simulate rice yields with respect to six different rates of N-fertilizer (40, 80, 100, 120, 140 and 160 kg/ha) in the study area. In the model simulation, total N-fertilizer rate was scheduled in three splits: 50% of total N-fertilizer as basal dose (i.e. at the time of transplanting), 25% at 20 days after transplanting (DAT) and the remaining 25% at 40 DAT. Table 5 shows the percentage change in rice yield and ΔY_{attain} with respect to different N-fertilizer application rates for three types of cultivars. An increase in N-fertilizer application increases the yield for the baseline period as well as all future periods. It is seen that the yield is increased significantly up to 140 kg/ha N-fertilizer in the study area irrespective of the cultivar type and after that the yield is increased slightly in response to additional N-fertilizer application. The results also revealed that rice yield could be increased by 14.6–17.3%, 5.7–7.5% and 4.0–5.2% for short, medium and long duration cultivars, respectively, at 140 kg/ha N-fertilizer application rate during the future period. At the same time, the average ΔY_{attain} of all cultivars was reduced from 0.73 to 0.53 t/ha in the study area. Past studies (Stuart *et al.* 2011; Patil *et al.* 2012; Doltra *et al.* 2014) reported that climate change will, directly and indirectly, change crop N-fertilizer demand, mineralization and leaching which will make N-fertilizer management even more challenging in the future than the present.

3.4.4. Selection of cultivar

The model simulation results also showed that the yield of each rice cultivar is reduced under the future climate scenario irrespective of the timing of transplanting. The reduction of yield due to climate change is found to be the lowest for the long duration cultivar (~0.25 t/ha), whereas it became double (~0.50 t/ha) for medium and short duration cultivars under current recommended practice as medium and short duration cultivars are more sensitive to rising temperatures under future climate scenarios (Rajwade *et al.* 2018). Among cultivars, the minimum yield reduction was found for PR106 (0.22 and 0.26 t/ha in 2030 and 2040s, respectively), whereas maximum reduction is expected to occur for Saket-4 (0.56 and

Table 4 | Response of the rice yield with respect to change in crop spacing

			Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)			Y_d (%)		
				RCP 8.5			RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**Adaptation strategies**	**Crop spacing**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
Saket-4	Reducing by 0.5 times	(10 cm × 10 cm)	4.97	4.89	4.80	2.86	2.30	2.24	1.12	1.61	1.60	35.5	48.4	48.3
	Reducing by 0.25 times	(15 cm × 15 cm)	4.32	3.81	3.75	2.46	2.27	2.22	1.00	0.78	0.78	16.6	46.5	47.0
	Increasing by 0.25 times	(25 cm × 25 cm)	2.87	2.42	2.35	2.01	1.76	1.70	0.29	0.18	0.18	−4.7	13.5	12.6
	Increasing by 0.5 times	(30 cm × 30 cm)	2.55	2.49	2.45	1.92	1.66	1.59	0.12	0.33	0.37	−9.0	7.1	5.3
	Baseline	(20 cm × 20 cm)	3.82	3.40	3.35	2.11	1.55	1.51	0.95	1.17	1.17			
Shankar	Reducing by 0.5 times	(10 cm × 10 cm)	4.74	4.98	4.99	2.64	2.15	2.11	1.15	1.83	1.88	39.7	54.7	57.5
	Reducing by 0.25 times	(15 cm × 15 cm)	4.09	4.77	4.80	2.23	1.86	1.80	1.04	1.96	2.04	18.0	33.8	34.3
	Increasing by 0.25 times	(25 cm × 25 cm)	2.81	2.67	2.61	1.73	1.31	1.24	0.52	0.83	0.85	−8.5	−5.8	−7.5
	Increasing by 0.5 times	(30 cm × 30 cm)	2.29	1.71	1.61	1.57	1.16	1.08	0.26	0.21	0.21	−16.9	−16.5	−19.4
	Baseline	(20 cm × 20 cm)	3.67	3.08	3.01	1.89	1.39	1.34	1.05	1.07	1.07			
IR36	Reducing by 0.5 times	(10 cm × 10 cm)	6.28	5.56	5.44	4.45	3.68	3.58	0.57	0.77	0.77	19.9	12.9	11.5
	Reducing by 0.25 times	(15 cm × 15 cm)	5.89	4.90	4.70	3.89	3.50	3.39	0.82	0.42	0.37	4.9	7.4	5.6
	Increasing by 0.25 times	(25 cm × 25 cm)	4.14	4.10	4.01	3.57	3.05	3.00	−0.26	0.23	0.21	−3.8	−6.4	−6.5
	Increasing by 0.5 times	(30 cm × 30 cm)	3.22	3.29	3.18	3.42	2.86	2.79	−0.84	−0.23	−0.25	−7.8	−12.3	−13.1
	Baseline	(20 cm × 20 cm)	5.31	4.97	4.77	3.71	3.26	3.21	0.54	0.72	0.61			
NDR-359	Reducing by 0.5 times	(10 cm × 10 cm)	5.83	5.90	5.82	4.19	3.33	3.20	0.47	1.39	1.46	24.0	13.3	10.3
	Reducing by 0.25 times	(15 cm × 15 cm)	5.44	5.59	5.43	3.46	3.03	2.90	0.89	1.44	1.44	2.4	3.1	0.0
	Increasing by 0.25 times	(25 cm × 25 cm)	3.73	3.29	3.18	3.21	2.64	2.58	−0.23	−0.01	−0.04	−5.0	−10.2	−11.0
	Increasing by 0.5 times	(30 cm × 30 cm)	3.72	3.10	2.88	3.05	2.44	2.35	−0.07	0.04	−0.05	−9.8	−17.0	−19.0
	Baseline	(20 cm × 20 cm)	4.75	4.30	4.22	3.38	2.94	2.9	0.42	0.50	0.48			
Swarna	Reducing by 0.5 times	(10 cm × 10 cm)	7.14	7.02	6.94	5.06	4.77	4.73	0.65	0.85	0.82	9.1	8.4	8.7
	Reducing by 0.25 times	(15 cm × 15 cm)	6.95	7.03	7.01	4.66	4.26	4.21	0.90	1.36	1.40	0.4	−3.2	−3.2
	Increasing by 0.25 times	(25 cm × 25 cm)	5.44	5.29	5.20	4.48	3.92	3.86	−0.13	0.31	0.30	−3.4	−10.9	−11.3
	Increasing by 0.5 times	(30 cm × 30 cm)	4.69	3.65	3.36	4.33	3.70	3.62	−0.58	−0.78	−0.93	−6.7	−15.9	−16.8
	Baseline	(20 cm × 20 cm)	6.82	6.10	5.91	4.64	4.4	4.35	0.82	0.48	0.38			
PR106	Reducing by 0.5 times	(10 cm × 10 cm)	6.96	6.84	6.72	4.67	4.46	4.38	0.90	1.01	1.00	10.9	11.8	10.9
	Reducing by 0.25 times	(15 cm × 15 cm)	6.73	6.63	6.49	4.25	3.75	3.70	1.13	1.55	1.49	1.0	−6.0	−6.3
	Increasing by 0.25 times	(25 cm × 25 cm)	4.90	4.79	4.75	4.11	3.49	3.37	−0.19	0.34	0.43	−2.4	−12.5	−14.7
	Increasing by 0.5 times	(30 cm × 30 cm)	4.10	3.85	3.76	3.94	3.21	3.07	−0.66	−0.13	−0.06	−6.4	−19.5	−22.3
	Baseline	(20 cm × 20 cm)	6.43	5.75	5.65	4.21	3.99	3.95	0.93	0.61	0.57			

Table 5 | Response of the rice yield with respect to change in N-fertilizer application rate in the study area

		Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)			Y_d (%)		
			RCP 8.5			RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**N-fertilizer application rate (kg/ha)**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
Saket-4	40	3.82	3.40	3.35	1.25	1.06	1.03	1.81	1.66	1.65	−40.8	−31.6	−31.8
	80	3.82	3.40	3.35	1.77	1.54	1.49	1.29	1.18	1.19	−16.1	−0.6	−1.3
	100	3.82	3.40	3.35	1.96	1.72	1.67	1.10	1.00	1.01	−7.1	11.0	10.6
	140	3.82	3.40	3.35	2.33	1.78	1.73	0.73	0.94	0.95	10.4	14.8	14.6
	160	3.82	3.40	3.35	2.40	1.84	1.77	0.66	0.88	0.91	13.7	18.7	17.2
	120	3.82	3.40	3.35	2.11	1.55	1.51	0.95	1.17	1.17			
Shankar	40	3.67	3.08	3.01	0.94	0.71	0.68	2.00	1.75	1.73	−50.3	−48.9	−49.3
	80	3.67	3.08	3.01	1.50	1.16	1.11	1.44	1.30	1.30	−20.6	−16.5	−17.2
	100	3.67	3.08	3.01	1.70	1.34	1.28	1.24	1.12	1.13	−10.1	−3.6	−4.5
	140	3.67	3.08	3.01	2.13	1.63	1.57	0.81	0.83	0.84	12.7	17.3	17.2
	160	3.67	3.08	3.01	2.22	1.74	1.66	0.72	0.72	0.75	17.5	25.2	23.9
	120	3.67	3.08	3.01	1.89	1.39	1.34	1.05	1.07	1.07			
IR36	40	5.31	4.97	4.77	1.75	1.46	1.44	2.50	2.52	2.38	−52.8	−55.2	−55.1
	80	5.31	4.97	4.77	2.38	2.04	2.01	1.87	1.94	1.81	−35.8	−37.4	−37.4
	100	5.31	4.97	4.77	3.03	2.61	2.58	1.22	1.37	1.24	−18.3	−19.9	−19.6
	140	5.31	4.97	4.77	3.93	3.47	3.39	0.32	0.51	0.42	5.8	6.4	5.7
	160	5.31	4.97	4.77	3.96	3.48	3.45	0.29	0.50	0.37	6.7	6.7	7.5
	120	5.31	4.97	4.77	3.71	3.26	3.21	0.54	0.72	0.61			
NDR-359	40	4.75	4.30	4.22	1.53	1.25	1.22	2.27	2.19	2.16	−54.7	−57.5	−57.9
	80	4.75	4.30	4.22	2.09	1.75	1.72	1.71	1.69	1.66	−38.2	−40.5	−40.7
	100	4.75	4.30	4.22	2.73	2.31	2.27	1.07	1.13	1.11	−19.2	−21.4	−21.7
	140	4.75	4.30	4.22	3.62	3.16	3.11	0.18	0.28	0.27	7.1	7.5	7.1
	160	4.75	4.30	4.22	3.65	3.14	3.1	0.15	0.30	0.28	8.0	6.8	6.9
	120	4.75	4.30	4.22	3.38	2.94	2.9	0.42	0.50	0.48			
Swarna	40	6.82	6.10	5.91	2.25	1.97	1.95	3.21	2.91	2.78	−51.5	−55.2	−55.2
	80	6.82	6.10	5.91	3.85	3.44	3.39	1.61	1.44	1.34	−17.0	−21.8	−22.1
	100	6.82	6.10	5.91	4.27	3.82	3.77	1.19	1.06	0.96	−8.0	−13.2	−13.3
	140	6.82	6.10	5.91	4.80	4.58	4.53	0.65	0.30	0.20	3.5	4.0	4.0
	160	6.82	6.10	5.91	4.93	4.56	4.49	0.53	0.32	0.24	6.3	3.6	3.2
	120	6.82	6.10	5.91	4.64	4.4	4.35	0.82	0.48	0.38			

(*Continued.*)

Table 5 | Continued

		Y_w (t/ha)			Y_a (t/ha)			ΔY_{attain} (t/ha)			Y_d (%)		
			RCP 8.5			RCP 8.5			RCP 8.5			RCP 8.5	
Cultivars	**N-fertilizer application rate (kg/ha)**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
PR106	40	6.43	5.75	5.65	2.02	1.72	1.69	3.12	2.88	2.83	−52.0	−56.9	−57.2
	80	6.43	5.75	5.65	3.46	3.01	2.95	1.68	1.59	1.57	−17.8	−24.6	−25.3
	100	6.43	5.75	5.65	3.86	3.39	3.32	1.28	1.21	1.20	−8.3	−15.0	−15.9
	140	6.43	5.75	5.65	4.40	4.19	4.15	0.75	0.41	0.37	4.4	5.1	5.2
	160	6.43	5.75	5.65	4.54	4.13	4.04	0.60	0.47	0.48	7.8	3.5	2.3
	120	6.43	5.75	5.65	4.21	3.99	3.95	0.93	0.61	0.57			

Table 6 | Percentage change in rice yield and yield gap with respect to cultivars under best adaptation options

		Adjusting transplanting date			**Adjusting crop spacing**			**Adjusting N-fertilizer**			**Combined adjustment of all**		
	Cultivars	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**	**Baseline period**	**2030s**	**2040s**
Rice yield (t/ha)	Saket-4	2.66	2.39	2.31	2.86	2.30	2.24	2.33	1.78	1.73	4.01	3.80	3.75
	Shankar	2.42	2.16	2.08	2.64	2.15	2.11	2.13	1.63	1.57	3.85	3.65	3.59
	IR 36	4.03	3.79	3.74	4.45	3.68	3.58	3.93	3.47	3.39	5.06	4.88	4.84
	NDR 359	3.60	3.34	3.30	4.19	3.33	3.20	3.62	3.16	3.11	4.71	4.51	4.48
	Swarna	4.96	4.79	4.77	5.06	4.77	4.73	4.80	4.58	4.53	6.18	6.05	6.04
	PR 106	4.58	4.43	4.40	4.67	4.46	4.38	4.40	4.19	4.15	5.84	5.74	5.70
Change in rice yield (%)	Saket-4	26.1	53.9	52.9	35.5	48.4	48.3	10.4	14.8	14.6	90.2	145.4	148.2
	Shankar	28.1	55.2	55.3	39.7	54.7	57.5	12.7	17.3	17.2	103.6	162.3	168.0
	IR 36	8.7	16.3	16.4	20.0	12.9	11.5	5.8	6.4	5.7	36.4	49.7	50.8
	NDR 359	6.4	13.8	13.8	24.0	13.3	10.3	7.1	7.5	7.1	39.3	53.3	54.4
	Swarna	6.8	8.9	9.6	9.0	8.4	8.7	3.5	4.0	4.0	33.2	37.5	38.9
	PR 106	8.8	11.0	11.3	11.0	11.8	10.9	4.4	5.1	5.2	38.7	43.8	44.2
Yield gap (t/ha)	Saket-4	0.70	0.50	0.52	1.12	1.61	1.60	0.73	0.94	0.95	0.05	0.13	0.16
	Shankar	0.71	0.42	0.42	1.15	1.83	1.88	0.81	0.83	0.84	0.07	0.15	0.17
	IR 36	0.81	0.53	0.37	0.57	0.77	0.77	0.32	0.51	0.42	0.07	0.14	0.16
	NDR 359	0.63	0.35	0.33	0.47	1.39	1.46	0.18	0.28	0.27	0.09	0.17	0.18
	Swarna	0.77	0.40	0.29	0.65	0.85	0.82	0.65	0.30	0.20	0.12	0.17	0.18
	PR 106	0.90	0.46	0.36	0.89	1.01	1.00	0.75	0.41	0.37	0.13	0.17	0.19

0.60 t/ha in 2030 and 2040s, respectively). As the yield is reduced by delayed transplanting as well as climate change, therefore earlier transplanting of each rice cultivar could be one preferred adaptation strategy for sustainable rice production that could reduce the yield gap in future. Monsoon rainfall is the only source of water for the rainfed rice cropping system in India, which heralds its appearance by the end of May. Therefore, the transplanting of the long duration cultivar may be shifted to 1st June. Medium duration cultivar may be preferred if transplanting is scheduled on 15th June and it is expected to be harvested by mid-October. Though the long duration cultivar transplanted on 15th June is likely to produce higher than the medium duration, it may hamper sowing of the following seasonal crop. The rice–wheat cropping system is the oldest and most prevalent agricultural practice in India (Singh & Kaur 2012). The studies on wheat crop in India (Sharma & Acharya 2000; Gill *et al.* 2009) found higher yield in the early sowing condition. The short duration cultivar may be selected if transplanting of rice is delayed further than 15th June due to unavailability of input resources. The short duration cultivar has several advantages over a long or medium duration crop as it requires less water availability, less exposure to hazards such as insects, pathogenic organisms, drouths and typhoons and increases the time the land would be available for subsequent plantings of other crops. It can be noted that delayed transplanting experiences more short-term water deficits at some point of time during the growing season (Debnath *et al.* 2018). Therefore, the adverse impact of climate change on rainfed rice cropping systems could be minimized by considering the timing of transplanting as 1st June, 15th June and 1st July for long, medium and short duration cultivars, respectively, under the future climate change scenario.

3.5. Rice yield response to best adaptation strategies

Considering a combination of transplanting timing, crop spacing, N-fertilizer application and cultivars as adaptation options, the model simulated results showed that optimum rice yield could be expected at (10 × 10) cm crop spacing, 140 kg/ha N-fertilizer application and scheduling transplantation at 1st June, 15th June and 1st July for long, medium and short duration cultivars, respectively, in the study area under future climatic projection. Therefore, this combination of adaptation strategies is considered the best with respect to all combinations of adaptation options considered in this study. The results revealed that the yield of the short duration cultivar is expected to be increased by 145.4–162.3% and 148.2–168.0% with respect to current recommended practice in the 2030s and 2040s, respectively, in the study area by using the best adaptation strategy (Table 6). Consequently, the average ΔY_{attain} of the cultivar is reduced from 1.12 to 0.14 t/ha and 0.16 in the 2030s and 2040s,

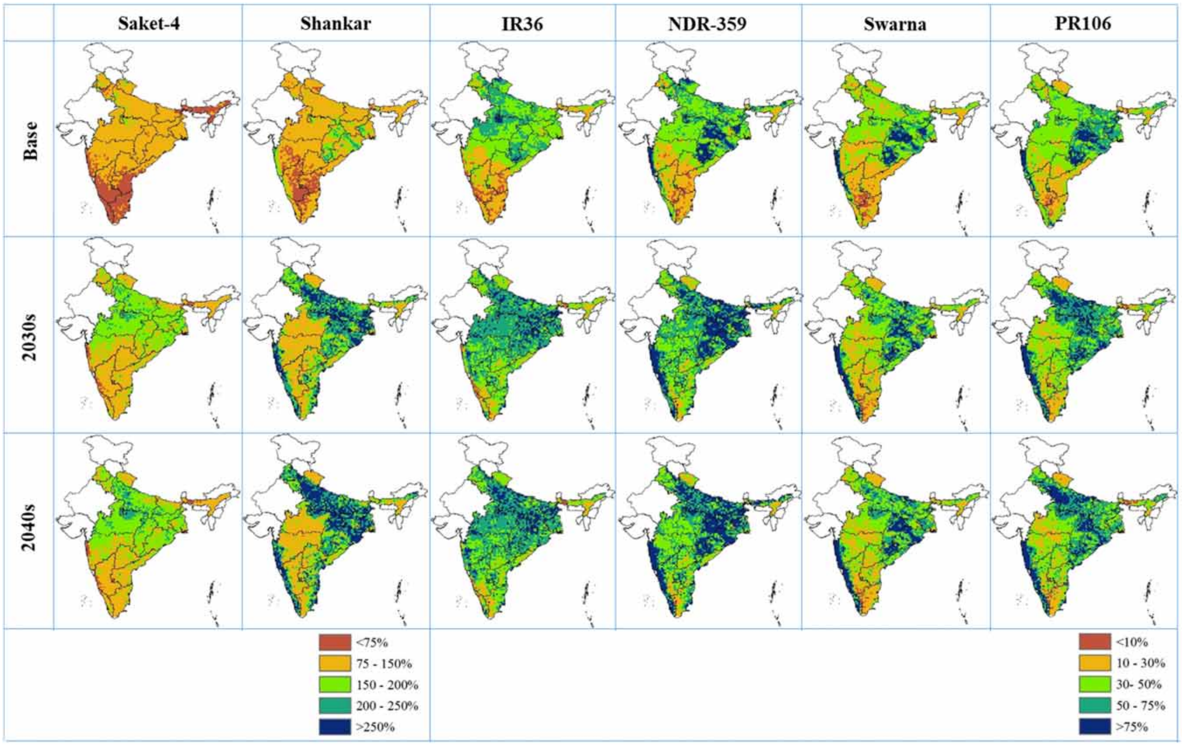

Figure 5 | Spatial variation of change in rice yield (%) by using best adaptation strategies in India.

respectively. For the medium duration cultivar and long duration cultivar, the average change in yield is expected to be 52.0 and 41.1%, respectively, in future. Figure 5 shows the spatial variation of change in rice yield with respect to cultivars using best adaptation options. The average $\Delta Y_{\mathrm{attain}}$ of all the cultivars are reduced from 0.76 to 0.16 t/ha and 0.71 to 0.19 t/ha by using the best adaptation options in two future periods. It could be noted that the rice yield could achieve 95.4–98.8% of the attainable yield of the cultivar by using the best combination of adaptation strategies.

4. CONCLUSIONS

The effectiveness of agronomic adaptation strategies to reduce the rainfed rice yield gap has been analyzed by using the DSSAT model in major rice-growing states of India. The study identifies the most promising adaptation strategy that could offer the best hope for meeting projected future food demand and sustain rice production. The equidistant quantile mapping technique was applied to correct bias in outputs of the RegCM4 model under the RCP 8.5 scenario and was used to project future climatic conditions. Four adaptation strategies including change in transplanting date, crop spacing, N-fertilizer application rate and type of cultivar were evaluated for the 2030s and 2040s. Future climate change may reduce the rice yield with an average of 0.42 t/ha among the studied rice cultivars under current recommended practice in the future. The combined effect of rising temperature and rainfall variability in future may be unfavorable to rice yield. The evaluation of adaptation strategies showed that advancing the transplanting date by fortnight for each cultivar, reducing the crop spacing to (10 × 10) cm and applying N-fertilizer at 140 kg/ha may increase the rice yield by 8.9–55.3%, 8.4–57.5% and 4.0–17.3%, respectively, in future. A combination of advancing transplanting timing (advancing by fortnight), reducing crop spacing (10 × 10 cm) and increasing N-fertilizer application (140 kg/ha) from the baseline is the best adaption strategy which increases rice yield by 37.5–168.0% and reduces the average attainable yield gap from 0.74 to 0.16 t/ha among cultivars in the study area under future climate change scenario. The results demonstrated that rice yield will be affected by climate change in the future and adaptation strategies have to be considered seriously. However, the feasibility of adaptation actions would depend largely on resource availability and farmers' mindset.

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CONFLICTS OF INTEREST/COMPETING INTERESTS

On the behalf of all authors, the corresponding author states that there is no conflict of interest.

CODE AVAILABILITY

The software used in this study is freely available on the open internet. The DSSAT model can be downloaded from https://dssat.net/.

AUTHORS' CONTRIBUTIONS

Subhankar Debnath conceptualized the article, organized data curation and software, conducted a formal analysis, and wrote the original draft. **Ashok Mishra** conceptualized the article, supervised, investigated, wrote the review and edited. **D.R. Mailapalli** conceptualized the article, supervised, investigated, wrote the review and edited. **N. S. Raghuwanshi** supervised, included funding acquisition, wrote the review and edited.

DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories. The climate data of different RCMs used in the study can be downloaded from http://cordex-ea.climate.go.kr/cordex/. The FAO soil information of the study area can be assessed through http://swat.tamu.edu/docs/swat/india%20dataset/FAO_%20soils.7z. The observed rice yield data (i.e. Table 1 of the article) can be downloaded from http://www.indiastat.com.

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