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Drought stress impacts of climate change on rainfed rice in South Asia

Tao Li[1] · **Olivyn Angeles**[1] · **Ando Radanielson**[1] · **Manuel Marcaida III**[1] · **Emmali Manalo**[1]

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Abstract Rice production is threatened by climate change and the productivity of rainfed rice is increasingly challenged. A better understanding of the future trends of rice production associated with climate change is important for improving food security. Rice production under irrigated and rainfed conditions was simulated using the rice crop model ORYZA2000. Simulated rice yield representing crop and environment interaction was used to evaluate the drought impact of climate change on rainfed rice in South Asia. If rainfed rice system was applied in all current rice cultivating areas in South Asia, drought stress could result to yield losses of more than 80 in 22 %, but crop failure was lower than 40 in 73 % of the areas under mild and severe SRES A1B and A2. The spatial patterns of drought stress on rainfed rice were similar under both A1B and A2, and the yield loss and crop failure decreased slightly in the far future (2045 to 2074) in areas where drought risk was high in the near future (2015 to 2044), but the impacts would gradually increase over initially low-impact areas. Both A1B and A2 would shift the best sowing season of rainfed rice to be earlier or later by up to 90 days in 30 years. Appropriate adjustment of sowing season is a major adaptation strategy for rainfed rice production in South Asia to benefit from climate change. In this case, rainfed rice yield could potentially increase by about 10 % in most areas of South Asia associated with 10 to 50 % lower inter-annual variation and slightly higher risk for crop failure.

1 Introduction

Climate change is threatening rice production. Recent researches confirmed that increasing air temperature with climate change results in the reduction of rice yield (Peng et al. 2004; Jagadish et al. 2007; Hasegawa et al. 2011). The change in rainfall pattern with increasing

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✉ Tao Li
t.li@irri.org; http://www.irri.org

[1] International Rice Research Institute, Los Baños, Philippines

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drought frequency and intensity decreases rice production (IPCC 2001; Passioura 2007). Drought stress can cause as much as 40 % loss in annual production in South and Southeast Asia (Pandey and Bhandari 2006; IRRI 2009), which translates to income losses of up to 58 % (Pandey and Bhandari 2007).

In contrast to the negative impacts of climate change, current researches also confirmed that elevated CO_2 with climate change can increase rice yield (Kimball et al. 2002; Kim et al. 2003; Yang et al. 2006; Taub 2010; Hasegawa et al. 2013), and improve water productivity through reduction in transpiration per unit of CO_2 assimilation (Allen et al. 1994; Kimball et al. 1995). The trade-off between positive and negative impacts of climate change attributes the variation of impacts on crop growth and yield to the local soil-climatic condition and crop management (Parry et al. 2004).

The threats of climate change on rainfed rice are more severe than on irrigated rice. About 23 million hectares of rainfed rice in South and Southeast Asia are most vulnerable to climate change (IRRI 2009). This underscores the necessity to understand the climate change impacts on rainfed rice to come up with strategies on alleviating the negative impacts and take advantage of the positive impacts in improving rice productivity and sustainability.

Crop models are effective tools in understanding the impacts of climate change on crop production (White et al. 2011; Mohandrass et al. 1995; Matthews et al. 1997; Masutomi et al. 2009). Modeling studies showed that climate change will cause a decrease in rice production in most areas, while increase may occur in special areas. However, the temporal changes in rice production were quantified by models with fixed cropping seasons over the continuum of climate change.

In this study, ORYZA2000 (Bouman et al. 2001) was employed to evaluate the drought stress impact of climate change on rainfed rice in South Asia. A computational algorithm was developed and used to quantify the effects of drought stress on rainfed rice yield with changing cropping seasons in response to climate change adaptation.

2 Material and methods

Drought impacts of climate change on rainfed rice over large spatial and temporal scales were evaluated for identified rice growing areas in South Asia, particularly Pakistan, India, Nepal, Bhutan, Bangladesh, and Sri Lanka, under SRES scenarios A2 and A1B in two 30-year periods of the near (2015 to 2044) and far (2045 to 2074) future.

2.1 Preparation of geographic data

The study region in South Asia is one of the major rice-producing regions in the world (Fig. S1, hereafter, the 'S' before table/figure numbers indicates supplementary material). The mean precipitation during the rainfed rice season in this region varies from less than 200 mm to more than 1000 mm in the near future. In the far future, the seasonal rainfall will decrease in southern and eastern South Asia but will increase in the northern and western areas.

The regional map of South Asia was converted into a grid map using ArcGIS. The map resolution was 5×5 arc-minutes, which was used for the presentation of the final results. The succeeding steps in this study were undertaken only for the grid cells with rice cultivation as identified by Gumma et al. (2011), referred to as 'rice cells'.

For all rice cells in the region, geo-coordinate referenced soil and weather data were prepared. Soil data on layer thickness, texture, bulk density, and organic carbon and nitrogen contents were extracted from the World Inventory of Soil Emission Potential (WISE) soil database, which has 5×5 Arc-minute resolution (Batjes 2006). The weather data of daily radiation, maximum and minimum air temperature, rainfall, humidity, and wind speed from 2015 to 2075 were downloaded from the projection from Coupled Global Climate Model (CGCM) for SRES A2 and A1B (www.cccma.ec.gc.ca/data/cgcm3/cgcm3.shtml) in 2.8 arc-degree grid. The CGCM projections were used in this study because 1) CGCM provided all daily weather data needed for simulations which the more reliable model ensemble projections could not provide, 2) the CGCM projections of spatial variability on temperature and precipitation were consistent with other climate models (Knutti and Sedláček 2012), and 3) the differences between the projections under SRES and RCPs were marginal (Rogelj et al. 2012).

2.2 Simulation of rice yield

Rice yield was simulated by ORYZA2000 v2.13 (https://sites.google.com/a/irri.org/oryza2000/downloads/download-now) under given crop management for each rice cell. ORYZA2000 has been well calibrated and validated with 91 rice genotypes in 32 locations in Asia (Li et al. 2009, 2013; Fig. S2 and Table S1). Compared with other rice models, individual or ensemble, ORYZA2000 provided consistent rice yield predictions with uncertainties comparable to the variation of field observations (Li et al. 2015). Similar to all other models, a better site-specific parameterization of crop management options and cultivars of the model would improve confidence in model simulations (Li et al. 2015; Muller et al. 2011). With robust calibration and validation, ORYZA2000 model offers reliable yield predictions to serve the purpose of this study. The study focused on understanding the relative change of rice production in continuous climate change regardless the absolute uncertainties from yield predictions.

Two groups of simulations were implemented for each rice cell to calculate yields under fully irrigated (IR) and rainfed (RF) conditions. Except for water management, agronomic practices in all simulations were completely the same: 10 cm rice field bund height; transplanted with 21-day-old seedlings; plant density of 1000 seedlings m^{-2} in the seedbed, and 25 hills m^{-2} with 2 plants per hill in the main field; no impact of pests and diseases; full nutrient and water supply in the seedbed; full nutrient supply in the main field. Full irrigation was applied in whole rice season in the IR, and the rainfed management was applied immediately after transplanting in the RF.

Simulated yield in IR (potential yield) was determined by incoming radiation, air temperature, and varietal characteristics, while simulated yield in RF (rainfed yield) was also affected by the possible drought stress resulting from low rainfall and/or low soil moisture under rainfed conditions. Each group of simulations involved 24 sowing dates year-round starting 1 January at 15-day intervals. Each of the 24 sowing dates was repeated for 60 years (2015 to 2074) from the available 61-year (2015 to 2075) weather information.

To estimate yields of all rice cells in South Asia, ORYA2000 used a virtual variety representing a combination of crop parameter traits. These traits included characteristics of drought-tolerant, rainfed, and upland rice varieties that have been calibrated and validated against field observed biomass and grain yield in earlier studies using the model (Li et al. 2009, 2013; Fig. S2), with growth duration varying between 100 and 125 days as typical upland and

rainfed rice cultivars currently used in South Asia. Saturated water conductivity and soil water holding capacity were derived using the method of Wösten et al. (2001).

All simulations were implemented under SRES A2 and A1B scenarios. A total of 5760 reruns were conducted for each rice cell using 24 sowing dates under fully irrigated and rainfed conditions. Grain yield at 14 % moisture content were used to compute drought indicators for the two 30-year periods in the next steps.

2.3 Evaluating the impact of climate change on rainfed rice

Four indicators, namely, relative drought impact (*RDI*), crop failure fraction (*CFF*), maximum rainfed grain yield (*MRGY*), and its coefficient of variation among seasons (*CVGY*), were computed from simulated yields to evaluate the impacts of climate change on rainfed rice for each rice cell in near and far future under A2 and A1B. For every rice cell in each period under each scenario, simulation outputs were organized into two data matrices, *P* and *A*, to represent potential and rainfed yields, respectively (Eqs. 1 and 2). In these matrices, p_{ij} and a_{ij} are the potential and rainfed rice yield, respectively, in year *i* and on sowing date *j*.

$$P = \left|p_{ij}\right| \quad (\mathrm{i} = 1, 2, 3, \cdots, \mathrm{m};\ \mathrm{j} = 1, 2, 3, \cdots,\ \mathrm{n}) \tag{1}$$

$$A = \left|a_{ij}\right| \quad (\mathrm{i} = 1, 2, 3, \cdots, \mathrm{m};\ \mathrm{j} = 1, 2, 3, \cdots, \mathrm{n}) \tag{2}$$

A zero value of $\boldsymbol{p_{ij}}$ indicates that the particular sowing date is not suitable for rice cultivation because of unsuitable temperature and/or solar radiation. If $\boldsymbol{p_{ij}}$ is zero, the $\boldsymbol{p_{ij}}$ and corresponding $\boldsymbol{a_{ij}}$ are excluded in the succeeding statistical analysis.

2.3.1 Relative drought impact (RDI)

For each rice cell, the standard difference (SD_{pa}) between potential (p_{ij}) and rainfed (a_{ij}) yields were calculated to represent the statistical deviation of the rainfed yields from the potential over all sowing dates in all years (Eq. 3).

$$SD\mathrm{pa} = \sqrt{\left(\sum_{j=1}^{n}\sum_{i=1}^{m}\left(p_{ij}-a_{ij}\right)^2\right)\Big/(n \times m-1)} \tag{3}$$

The SD_{pa} represents only the effects of drought stress on rice production in a given location across temporal scales. Values of SD_{pa} for locations cannot be used to compare impacts at a spatial scale. Hence, the ratio of SD_{pa} to the potential yield (Eq. 4) was calculated to indicate relative drought impact (*RDI*). This was used to compare the drought impacts of different soil-climatic conditions over spatial scale:

$$RDI = SDpa\Big/\sqrt{\left(\sum_{j=1}^{n}\sum_{i=1}^{m}\left(p_{ij}\right)^2\right)\Big/(n \times m-1)} \tag{4}$$

RDI approximates the value 1.0 if $\boldsymbol{a_{ij}}$ approximates to zero, implying that severe drought stress (or no rainfall) occurred in a given location. In contrast, *RDI* approaches zero when $\boldsymbol{a_{ij}}$

approximates $\boldsymbol{p_{ij}}$, which implies that no drought stress occurred in the specific location under rainfed conditions.

A smaller value of *RDI* therefore implies a smaller impact of drought stress or that drought stress does not significantly reduce grain yield in a location under rainfed conditions in a given climate change scenario. *RDI* is a general indicator of drought stress for rainfed rice over temporal and spatial scales.

To quantify the change of drought impact between the far to near future periods, ΔRDI in percentage was computed using Eq. 5, where RDI_1 and RDI_2 were the values of *RDI* in the near and far future periods, respectively.

$$\Delta RDI = \frac{RDI_1 - RDI_2}{RDI_1} \times 100 \tag{5}$$

2.3.2 Crop failure fraction (CFF)

CFF measures the probability of crop failure caused by drought stress for all tested sowing dates in 30 years. Crop failure means that no grain yield is harvested from a location under rainfed conditions, whereas, grain yield is larger than zero under fully irrigated conditions. *CFF* is an indicator of extreme drought stress over temporal scales in a given location.

To calculate the *CFF* of each rice cell, a new matrix ($A^{'}$) was derived from matrix A to represent all $\boldsymbol{a_{ij}}$ with a value of 0.0 in A. With $A^{'} \in A$, *CFF* is the ratio of the number of elements in $A^{'}$ ($[A^{'}]$) to those in $A([A])$ (Eq. 6).

$$CFF = \left[A^{'}\right]/[A] \tag{6}$$

Low value *CFF* represents lower chance of extreme drought stress and implies that rainfed rice is safer for the given location, while a high value *CFF* indicates that the rice crop frequently suffers extreme drought stress and has higher risk of complete crop failure under rainfed conditions. Variability of *CFF* values among locations also represents the spatial variations of extreme drought stress. Similar to ΔRDI, ΔCFF was calculated from *CFF*.

2.3.3 Maximum rainfed grain yield (MRGY) and its coefficient of variation (CVGY)

For each rice cell, *CV* is a one-dimensional matrix of $\boldsymbol{cvgy_j}$ (Eq. 7), where the value of $\boldsymbol{cvgy_j}$ is the coefficient of inter-annual variation in rainfed rice yield for j^{th} sowing date as calculated in Eq. 8 from the data matrix A (Eq. 2). In Eq. 8, the $\overline{a_j}$ is the mean of $\boldsymbol{a_{ij}}$ for j^{th} sowing date over many years ($\boldsymbol{i}$), and $\boldsymbol{m}$ is the number of years with $\boldsymbol{a_{ij}}$ values corresponding to $\boldsymbol{p_{ij}}$ values greater than zero.

$$cv = \left|cvgy_1, cvgy_2, \cdots, cvgy_j\right| \quad (\mathrm{j} = 1, 2, 3, \cdots, \mathrm{n}) \tag{7}$$

$$cvgy_j = \sqrt{\left(\sum_{i=1}^{m}\left(a_{ij} - \overline{a_j}\right)^2\right)/(m-1)}/\overline{a_j} \tag{8}$$

Ideally, the highest $\overline{a_j}$ associated with the lowest $\boldsymbol{cvgy_j}$ would be the best representative of rice productivity under rainfed conditions in a specific rice cell. However, a single best representative may not exist. In this case, the top three values for $\overline{a_j}$ corresponding to three different sowing dates were considered. Among the three $\boldsymbol{cvgy_j}$ values corresponding to the top three $\overline{a_j}$ values, the lowest $\boldsymbol{cvgy_j}$ identifies the $\overline{a_j}$ that would represent a given rice cell. This representative $\overline{a_j}$ is the maximum rainfed grain yield (*MRGY)*, and the corresponding $\boldsymbol{cvgy_j}$ is the typical coefficient of variation for rainfed grain yield (*CVGY*). The corresponding sowing date for the *MRGY* is the best sowing date for rainfed rice (*BSS*) for this specific rice cell. Like *ΔRDI* and *ΔCFF*, the *ΔMRGY* was also calculated for near to far future periods. The *ΔBSS* was the change in days of *BSS* of far from near future.

2.3.4 Temporal changes of drought stress in SRES scenarios

The values of *ΔRDI*, *ΔCFF*, *ΔMRGY, ΔCVGY* and *ΔBSS* calculated from above processes were also determined for each of A2 and A1B to understand the differences of temporal changes of drought stress under these two SRES scenarios.

3 Results

3.1 Performance of ORYZA2000 for rice genotypes in multiple environments

ORYZA2000 estimated irrigated and rainfed rice yields with uncertainties of 23 to 25 % (Table S1) with more than 95 % of the predictions within the confidence levels defined by the standard deviation for field measurements (Fig. S2). Having reliable rice yield predictions (Supplementary Text 1), ORYZA2000 offers a new approach to evaluate the drought stress impact of climate change on rainfed rice, and to determine the best sowing date at which the high and stable yield can be achieved. Additional simulations for three sub-regions demonstrated the reliability in which the best sowing dates determined by the model using historical weather data were highly consistent with current sowing date reported in literatures (Fig. S3, Supplementary Text 2).

3.2 Relative drought impact (RDI)

RDI characterized drought stress severity with climate change. It had a similar spatial pattern over South Asia under both A2 and A1B ranging from 0.04 to 0.99 (Fig. 1a and b). This implies that drought stress reduced rice yield under rainfed conditions in all rice areas within South Asia regardless of sowing date and climate scenario. The A1B and A2 did not result to significant differences in *RDI* in most areas. However, scenario A2 slightly increased drought stress in the middle and northwest corner of South Asia, but decreased in north-central areas (Fig. 1a and b).

Under climate change, 48 % (A2) and 50 % (A1B) of the total rice area (Fig. 1c) located in the northeastern and scattered in the southern and middle east areas of South Asia (green to light yellow dots in (Fig. 1a and b), had minor drought stress where rainfed rice yield could surpass 50 % of the potential yield (*RDI≤0.5*). In contrast, 22 % (A2 and A1B) of the total rice area suffered from extreme drought stress where yield could reach only 20 % of the potential yield (*RDI> 0.8*) (Fig. 1c, and red dots in Fig. 1a and b). This occurred mainly in the west, and

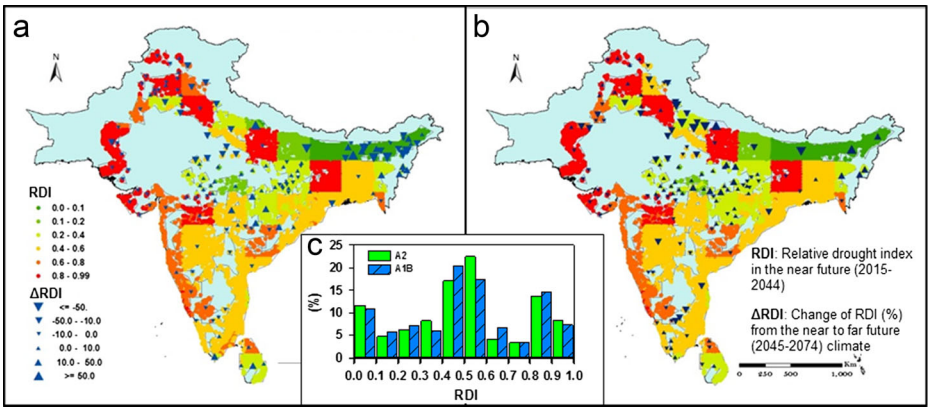

Fig. 1 Spatial pattern of the relative drought index (*RDI*) of rainfed rice (*colored areas*) in the near future (2015–2044) and the change of *RDI* (*blue triangles*) between the two 30-year periods (2015–2044 and 2045–2075) under climate change scenarios A1B (**a**) and A2 (**b**). The histogram (**c**) represents the differences of *RDI* frequencies between A1B and A2 from 2015 to 2074

in some north and eastern inland areas of South Asia. Drought stress was lower in south and east areas than in north and west areas.

Drought stress in the far future decreased by 10 to 50 % in the areas suffering from extreme drought stress in the near future, but increased by 10 to 50 % in the areas of moderate drought stress under both SRES scenarios (Fig. 1a and b). In the northeastern areas of South Asia, where only minor drought stress existed in the near future, drought stress changed significantly by more than ±50 % in different sub-areas under scenario A2 while scenario A1B resulted in an increase or decrease by 10 to 50 %.

3.3 Crop failure fraction (CFF)

CFF characterized the probability of extreme drought stress occurrence leading to crop failure. The 73 % of total rice area (A2 and A1B) had lower than 0.4 mean *CFF* over the next 60 years (Fig. 2c). Less than 1 % of the total rice area had a high risk of crop failure (*CFF*>0.7), mainly in northwestern areas (Fig. 2a and b).

The *CFFs* increased up to 10 % in far future compared to the near future in most areas of South Asia, where the *CFFs* were relatively lower. In contrast, the *CFFs* significantly decreased (>10 %) in the far future in the areas where the *CFF*s were high in the near future (Fig. 2a and b).

Comparing Figs. 1 and 2, western South Asia was a high-risk region for rainfed rice because of the high *RDI*s and *CFF*s. Eastern and southern areas had a very low risk of complete crop failure as *CFF* was generally lower than 0.06, but a significant yield loss would be expected in a few sub-areas ($0.4 \leq RDI \leq 0.6$) (Fig. 2).

3.4 Maximum rainfed grain yield (MRGY) and its coefficient of variation (CVGY)

In the near future, *MRGY* varied to a great extent from 0.26 to 9.4 t/ha across current rice areas in South Asia with similar spatial patterns in A2 and A1B (Fig. 3a and b). The *MRGYs* were in the range of 2 to 6 t/ha in the south, lower than 2 t/ha in the west, and higher than 6 t/ha in the northeast of South Asia. The *CVGY* of *MRGY*, varied from lower than 0.05 to higher than 0.6

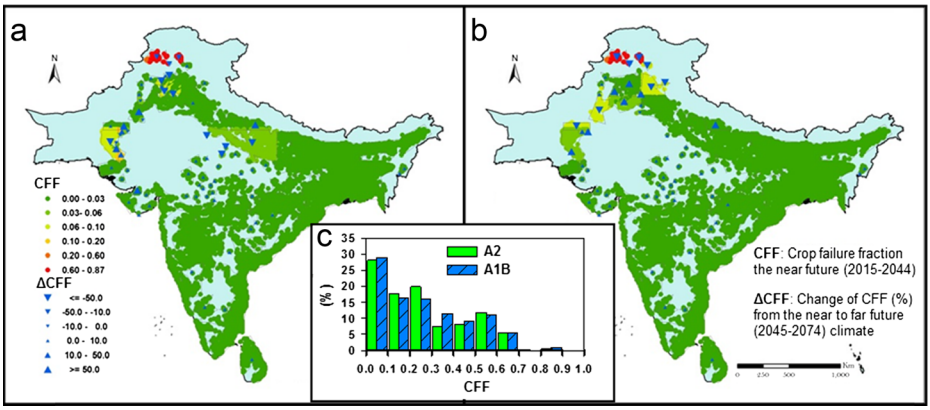

Fig. 2 Spatial pattern of the crop failure fraction (*CFF*) of rainfed rice (*colored areas*) in the near future (2015–2044) and the change of *CFF* (*blue triangles*) between the two 30-year periods (2015–2044 and 2045–2075) under climate change scenarios A1B (**a**) and A2 (**b**). The histogram (**c**) represents the differences of *CFF* frequencies between A1B and A2 from 2015 to 2074

(Fig. S4a and b). *CVGY* was lower than 0.1 in most areas, while a high *CVGY* (>0.6) occurred in areas where *MRGY* was lower than 1 t/ha (Figs. 3 and S4). Comparing *CVGY* between the two SRES scenarios, A2 obviously increased *CVGY* in western and northern South Asia.

In the far future, *MRGY* increased in most areas, where the changes from the near to far future were similar under both A2 and A1B over South Asia (Fig. 3a and b). Rainfed rice was threatened by climate change (indicated by significant decrease in *MRGY*) but only in a few scattered locations. From near to far future, climate change resulted to significant yield increases in areas with high drought stress but lower crop failure (Figs. 1, 2, and 3). *CVGY* declined by more than 10 % in almost all rice areas but decreased more under A2 than under A1B (Fig. S4a and b). Majority (77 %) of the rice areas had *MRGY* higher than 3 t/ha (Fig. 3c), and 82 % (A1B) and 78 % (A2) of the rice areas had less than 10 % inter-annual variation in

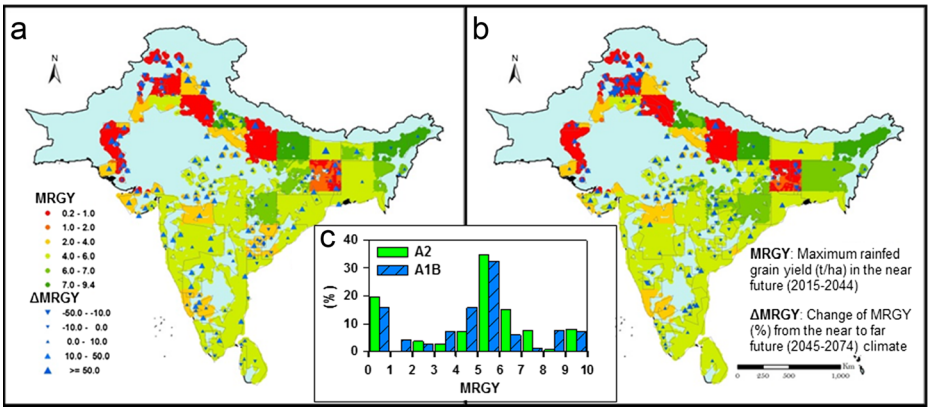

Fig. 3 Spatial pattern of the maximum rainfed rice grain yield (*MRGY*, t/ha) (*colored areas*) in the near future (2015–2044) and the change of *MRGY* (*blue triangles*) between the two 30-year periods (2015–2044 and 2045–2075) under climate change scenarios A1B (**a**) and A2 (**b**). The change was the yield difference among the best sowing seasons from the two 30-year periods. The histogram (**c**) represents the differences of *MRGY* frequencies between A1B and A2 from 2015 to 2074

MRGY. In summary, climate change gradually increased rainfed rice yield and reduced the inter-annual variation in yield if the sowing season was adjusted accordingly.

3.5 Best sowing season (BSS) of rainfed rice

The *BSS* of rainfed rice defined by simulated yields (Section 2.3.3) was generally in the second quarter of the year (April to June) in the northern and southern end, but occurred later (June to August) along the middle latitude of South Asia. There were no differences in *BSS* between A1B and A2 in most rice areas in the near future (Fig. 4a and b). However, as climate changes from the near to far future under A1B, the *BSS* was significantly shifted by 15 to 90 days earlier in the northern and middle areas, and was significantly delayed by ≥90 days in the southern South Asia (Fig. 4a). Similarly, under scenario A2, the *BSS* in the northern South Asia was shifted to an earlier time in the year, and delayed by less than 15 days in the southern South Asia (Fig. 4b). The changes of *BSS* could alleviate possible threats of drought caused by climate change in most areas of South Asia as indicated by positive *ΔMRGY* (Fig. 3).

4 Discussion

4.1 Drought stress indicators as measure of climate change impacts on rainfed rice

Annual and inter-annual (temporal) variations in potential and rainfed rice yields presented a complex pattern (Fig. S5). Consequently, the spatial and temporal variability of drought impact among rice cells were also observed under future climate scenarios (Supplementary Text 3). Among the four indicators, *RDI* is the most independent of crop characteristics and represents the water-limited production in proportion to potential production. *RDI* is mainly subjected to local soil-climactic conditions while the other three indicators (*MRGY*, *CVGY*, and *CFF*) are dependent on crop characteristics and strongly represent the interactions of the crop and its environment. The *CFF* indicates the severity of drought stress in causing complete crop failure

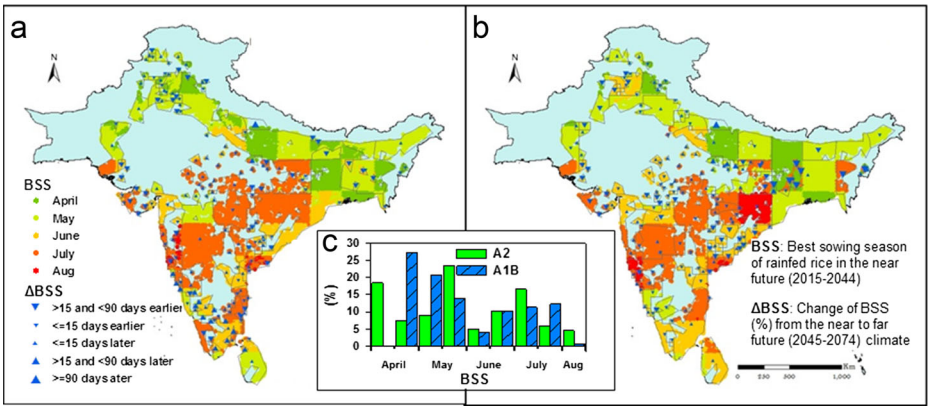

Fig. 4 Spatial pattern of the best sowing season (*BSS*) for rainfed rice (*colored areas*) in the near future (2015–2044) and the shifts of *BSS* (*blue triangles*) between the two 30-year periods (2015–2044 and 2045–2075) under climate change scenarios A1B (**a**) and A2 (**b**). The histogram **(c)** represents the differences of *BSS* frequencies between A1B and A2 from 2015 to 2074

and the *MRGY* with its corresponding *CVGY* represent drought stress during the best sowing season. Since the same virtual rice cultivar was used for all years and all rice cells, spatial variation of these indicators mainly resulted from the differences in soil-climatic environments and their varying interaction with the crop under rainfed conditions.

An on-going simulation exercise (unpublished data) showed that the uncertainties of drought stress indicators would range from 3 to 30 % and vary among rice cells if downscaled climate data was used. This underscored that further studies are essential to address the complexity of uncertainties attributed to downscaling, which is currently outside the scope of this paper.

4.2 Climate change and rainfed rice in South Asia

With the assumption that the CGCM projections are valid[1] over the rice areas in South Asia, the similar amount and spatial distribution of rainfall in the near future under both A1B and A2 (Fig. S1a, b, and c) resulted to similar drought impact on rainfed rice during the first 30 years (Figs. 3 and 4).

As climate change progresses from near to far future, the changes in the amount of seasonal rainfall differed between A1B and A2 scenarios within South Asia (Fig. S1d, e, and f). Generally, rainfall increased in areas where rainfall was initially low and decreased in areas where rainfall was initially high in the near future. Simulation results showed that *RDI* declined in areas where drought impact was initially high in the near future for the following reasons: 1) rainfall increased in some dry areas; and 2) the elevation of CO_2 increased the use efficiency of water (Ainsworth and Rogers 2007; Taub 2010). However, drought impact on rainfed rice increased in areas where it was initially low because of unchanged rainfall. More than 80 % of rice areas had seasonal rainfall higher than 400 mm, and the slight increase in seasonal rainfall could be expected in more than 60 % of the rice areas as climate change continues (Fig. S1), thereby, decreasing the risk of complete crop failure for rainfed rice over South Asia. Climate change could be beneficial to rainfed rice production in South Asia if the rainfed rice season would be adjusted accordingly (Figs. 3, 4 and S4). It also implies that CO_2 fertilization effects could potentially overcome the expected yield reduction caused by the increase in air temperature (Baker et al. 1992; Matsui et al. 1997; Ainsworth and Ort 2010). This result was inconsistent with earlier evaluations that climate change may result in slight (~6 %, Soora et al. 2013) or significant (15–17 %, Aggarwal and Mall 2002) decreases of rainfed rice production in India, or 'no effect trends' in rice yield (Knox et al. 2012) (Supplementary Text 4).

This study demonstrated that the positive effect of climate change on rainfed rice only applies when the best sowing season was utilized (Fig. 4), which changed significantly throughout South Asia. The sowing seasons for future climate suggested by the simulation results of this study might differ from the current farming practices in the study area. Hypothetically, assessment results would also be different if varieties with different drought tolerant traits or crop growth duration were applied in different regions (Li et al. 2013). Nonetheless, this study proved that the adjustment on sowing season of rainfed rice is essential to adapt to climate change. It is consistent with the reviews on climate change effects in South

[1] All analyses conducted were based on CGCM projections. The accuracy of the CGCM projections is beyond the scope of this paper.

Asia that recommended shifting planting dates (at individual level) as an adaptive strategy, which needs adoption of improved varieties and improved rice cultivation technologies to be more significant (Knox et al. 2012).

5 Conclusions

Using the simulation results of ORYZA2000 with four indicators relative drought impact (*RDI*), crop failure fraction (*CFF*), maximum rainfed grain yield (*MRGY*), and the coefficient of inter-annual variation in grain yield (*CVGY*), a comprehensive evaluation approach was used to substantially understand the impacts of climate change on future rainfed rice production and provide information for the adaptation of rice production to climate change.

As climate changes from near to far future, the impact of drought on rainfed rice would gradually increase over initially low-impact areas and decrease in initially high-impact areas. The chance of complete crop failure for rainfed rice was expected to gradually decrease in South Asia, and severe and mild SRES scenarios (A2 and A1B) would not have significantly different drought impacts on rainfed rice.

The threat of drought caused by climate change could be alleviated by adjusting the sowing season of rainfed rice according to future climate conditions, particularly rainfall. The timely and reasonable choice of sowing season could ensure no significant yield reduction for 90 % of total rice areas, and the maximum grain yield of 4 to 6 t/ha attainable for rainfed rice in most areas of South Asia.

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