Article

Planting *aman* rice at monsoon onset could mitigate the impact of temperature stress on rice-wheat systems of Bihar, India

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Abstract: The rice-wheat rotation is the dominant cropping system in Bihar, where food security of the rural population depends heavily on the production of rice and wheat. In Bihar, climatic shocks induced by low temperatures and terminal heat stress can significantly affect rice and wheat yields. The present work evaluates the benefit of using the monsoon onset as the date for planting rice in reducing thermal stress on rice-wheat systems. High-resolution gridded crop simulations using the APSIM model were performed to simulate potential yields of rice and wheat using the monsoon onset and the farmers' practice as planting dates. The monsoon onset was calculated using an agronomic definition and farmers' practice dates were estimated using satellite data. Model outputs were analyzed in terms of planting dates, yields, and the incidence of low temperature stress on rice and high temperature stress on wheat by means of the APSIM yields limiting factors. The results show that the rice planting and harvest dates using the monsoon onset are in general 20-30 days earlier, decreasing the incidence of thermal stress in rice and wheat, and generating higher and more stable yields. These results can help design mitigation strategies for the impacts of climate shocks induced by low and high temperature events in the context of the advances in sub-seasonal and seasonal forecasting, targeting climate services for farmers in Bihar.

Keywords: South Asian monsoon; rainy season, TIMESAT, APSIM, crop modeling, climate adaptation

1. Introduction

Agriculture is a vitally important sector for the dominant rural population of North India and in general over the Indo-Gangetic Plains (IGP) of South Asia, sustaining local economy, employment, and livelihoods. This region is known for being a major food supply for India, being extremely important for food security, providing staples such as rice and wheat to the rest of the country, among other cereals and vegetables [1]. However, the steady population increase and the existing environmental stressors impose multiple challenges to the sustainable food production and security in South Asia [2]. Rice-wheat corresponds to the main cropping system in the IGP, which is grown in a crop rotation that begins with rice seedlings sown in seedbeds, which are subsequently planted in the field (transplanting) after the arrival of the monsoon rains (*kharif* season). Rice is followed by wheat cultivation during the dry season in winter (*rabi* season). A total area of about 13.5 million of hectares sustain this system over the IGP, on which about 50% of all grains in India are produced [3]. However, a slowdown in the increase in productivity of rice-wheat systems has been observed in recent decades, which has generated concern from the point of view of food security, and therefore, new strategies to counteract this decline in productivity seem necessary [4].

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Despite geographic and cultural similarities in the Indian IGP, important differences exist between the West, central, and East area in terms of agro-ecological gradients of climate [5] and soil [6], as well as in socioeconomic features such as rural livelihoods [7]. As a consequence of a lower access to relevant inputs such as irrigation and fertilizers, these differences translate into a higher wheat and rice yield gap and food insecurity over the Eastern IGP [7,8]. This is the case of the state of Bihar, where poverty and malnutrition prevail on the dominant smallholder rural population, to which agriculture provides employment to near 54% of the total workforce [1]. The dominant rice-wheat cropping system reached a total 5.4 million hectares in 2017-2018 in Bihar, producing a total of 14.2 million tons [3]. However, the growth of the agricultural sector of Bihar in recent decades has been lower than the rest of the country [1], and factors such as smaller farm sizes and lower crop intensity, and less access to irrigation and agricultural inputs lead to higher regional rice-wheat yield gaps [8].

In addition to the low historical crop yields in Bihar and in general in the Eastern IGP, recurring climate-related adverse events such as droughts, floods, and thermal stress due to low and high temperatures during sensitive plant stages have led to high volatility in agricultural productivity of smallholder farmers [1]. The latter is highly relevant given the condition of staple food of rice and wheat and the regional susceptibility to adverse events leading to crop productivity drops. In this sense, multiple sources of uncertainty and factors affecting crop yields threaten food production, where climate variability and change [9], groundwater depletion [10], and air pollution [11], are major concerns for food security and population.

Much attention has been paid to summer monsoon rains and mean temperatures variability over the IGP as determinants of crops productivity [5,12]. However, less emphasis has been placed on the impacts of adverse temperatures on rice-wheat systems and on the development of adaptation strategies based on management decisions. In this regard, both low and high temperatures can negatively impact the productivity of rice and wheat by affecting multiple physiological processes [13]. For instance, a late monsoon onset and the consequent delayed rice planting may result in rice yield losses due to spikelet sterility induced by low temperatures at the end of the rainy season [14]. Closely connected with the above, a delayed wheat harvest induced by a late sowing exposes the spikes to high temperatures during the gran filling stage, reducing yields due to the terminal heat stress [15]. Studies performed in the IGP show that an earlier wheat sowing can reduce the impact of terminal heat stress [15]; however, to date, regional-scale studies have not been performed in Bihar in order to evaluate the benefits of changes in planting and sowing dates on rice-wheat yields by reducing thermal stress. The foregoing is relevant considering that the adjustment in both rice planting and wheat sowing dates strongly influences the rice-wheat yields achieved over East India [16].

Previous studies have shown the impact of anomalously low and high temperatures on rice and wheat productivity in Bihar [17], suggesting that actionable adaptation strategies are needed as future climate change projections over the region show a clear increase in thermal stress conditions for crops [18]. In this regard, adaptation strategies to cope with the impacts of climate variability on rice-wheat systems range from breeding for more tolerant cultivars, short-duration cultivars, irrigation and water management, and rescheduling of planting dates [15]. Water management options are often adopted to mitigate the impact of thermal stresses, being the use of irrigation commonly implemented to prevent both the strong drop in temperature during the sensitive stages of rice, and to maintain relatively low temperatures to avoid terminal heat stress in wheat [13]. Following the later, this work aims at evaluating the shifting of rice planting date, a practice that farmers can relatively easily adopt as a strategy to mitigate the impact of temperature-related stress in rice-wheat systems [14]. The earlier planting of rice and sowing of wheat have been recommended to reduce the damage caused by low temperatures in rice [13] and heat stress on wheat [15], respectively. In the Eastern IGP, the seedbed preparation for rice nursery begins at the time of the first monsoon rains and 20-30 days later the seedlings are transplanted to the puddles. Therefore, a delay in the onset of the monsoon rains

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can lead to a delay in the planting and harvesting of rice, and consequently in the sowing and harvesting of wheat, thus exposing rice to low temperatures [20] and wheat to terminal heat stress during grain filling [15].

In view of the need of developing regional-scale strategies for adaptation to climate variability and change over agricultural areas of high social and environmental vulnerability such as the state of Bihar in India, this study aims to evaluate the use of the monsoon onset as a criterion for rice planting date in terms of the mitigation of the impact of climatic shocks due to low and high temperatures stress in rice and wheat, respectively. The study is based on the use of a gridded crop modeling approach to evaluate two rice planting date scenarios: the farmers' practice, estimated from satellite data, and the monsoon onset calculated using an agriculturally relevant definition. The two planting scenarios are evaluated in terms of the potential productivity and the occurrence of thermal stress conditions for rice-wheat system in Bihar.

2. Materials and Methods

2.1. Study area

The study area corresponds to the state of Bihar in North India (Figure 1). Located in the eastern IGP of South Asia, Bihar is a densely populated area where the main economic activity is agriculture and 54.4% of the population lives below the poverty line [3]. While farming systems in Bihar are diverse, the main cropping system corresponds to the rice-wheat rotation, being cereals the main staple food. Rice is cultivated over 3.28 million hectares in 2017-2018 [3] during the monsoon or *kharif* season (June-October), and wheat over 2.04 million hectares in winter or *rabi* season (October-April) [3]. In 2017-2018 Bihar produced 7.91 million tons of rice and 5.74 million tons of wheat [3]. Other crops such as maize, oilseeds and potato are also grown.

Climate in Bihar is characterized by hot and humid summers and cold and dry winters. The monsoon rains concentrate typically from mid-June and late September. Climate variability and seasonality are major determinants of agricultural productivity in Bihar. Given the dominant rainfed conditions of rice-wheat systems, while the productivity of the dominant *kharif* rice is highly determined by anomalies in monsoon rains, temperatures strongly determine the productivity of wheat in winter [12,17].

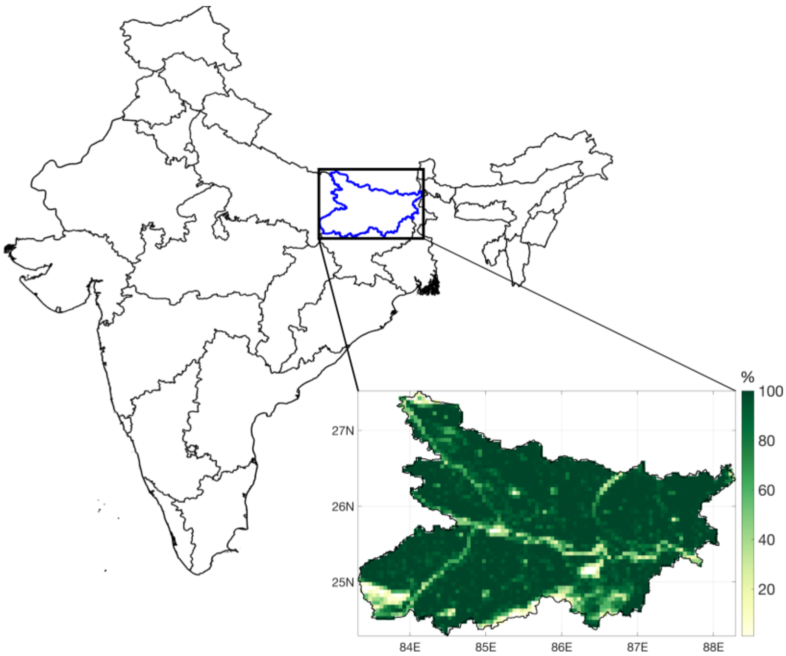

Figure 1. Map of India showing the location of the state of Bihar. Black lines delimit the states. Zoomed area corresponds to the percentage of croplands in Bihar according to the MODIS MCD12Q1 product.

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2.2. Datasets

2.2.1. Satellite Normalized Difference Vegetation Index

The Advanced Very High-Resolution Radiometer (AVHRR) Global Inventory Modelling and Mapping Studies (GIMMS) Normalized Difference Vegetation Index (NDVI) NDVI3g v1 product for the period 1982 through 2015 was used to extract phenological records [21]. In the present work, the onset of the growing season was extracted, as explained below. NDVI3g has been widely used in multiple vegetation studies, including trends in greening and phenology [22], land use classifications [23], among others. NDVI3g is generated from AVHRR by incorporating corrections and normalizations to account for atmospheric effects, sensor calibration issues, and orbital drift. Its spatial resolution is 1/12º (~8 km), and it is provided as biweekly (15-days) composites. In this work, the original 1/12º resolution was bilinearly reprojected to a 0.05º grid to match the resolution of the meteorological data, presented below.

2.2.2. Meteorological data

Daily precipitation data for the period 1982 through 2015 from the Climate Hazards Group Infrared Precipitation with Station data (CHIRPS) [24] V.2 were used. Developed by the Santa Barbara Climate Hazards Group at the University of California, CHIRPS V.2 corresponds to high-resolution (0.05º × 0.05º) satellite-derived daily rainfall dataset available from 1981 to present. CHIRPS is generated by combining multiple sources, including the Tropical Rainfall Measuring Mission (TRMM) [25] and ground measurements.

Along with the CHIRPS product, additional daily meteorological data from the last generation ERA5 atmospheric reanalysis were used. ERA5 is developed by the European Centre for Medium-Range Weather Forecasts (ECMWF), and provides data both at an hourly and monthly time scale with a horizontal resolution of 0.25º × 0.25º (~31 km) for the period 1979 to present, and for single (surface) and multiple vertical levels [26]. In this work, daily maximum and minimum air temperature (2-m above ground) and daily solar radiation data were used, which were aggregated from hourly ERA5 data.

2.2.3. Soil data

Data from the Global Soil Dataset for use in Earth System Models (GSDE) [27], the SoilGrids product [28], along with the Harmonized World Soil Database [29] were used. These datasets provide information on soil physical (textures, bulk density) and chemical properties (total N, organic C), among other variables, necessary for crop modeling.

2.3. Rice planting date scenarios

Two rice planting date scenarios were evaluated. First, the common farmers' rice planting date (hereafter farmers' practice) was estimated using satellite data and a phenology metrics algorithm. As a second scenario, the date of the monsoon onset was used. Monsoon onset was calculated using an agronomic local definition, which was then used as a date parameter for rice planting. Details on how these dates ware obtained are presented below.

2.3.1. Farmers' practice rice planting date

Farmers' practice rice planting dates over Bihar were estimated using the AVHRR NDVI time series (Section 2.2.1) and the TIMESAT Savitzky-Golay smoothing method [30]. The start of the season parameter was calculated for the monsoon onset transition period from the smoothed NDVI using the TIMESAT software package. An increase in NDVI of 20% of the seasonal amplitude was considered as the start of a season, starting from its minimum during the dry season to the maximum green-up during the wet period in summer. The rice planting date was assumed to occur 20 days before the start of the season calculated from TIMESAT [31].

2.3.2. Monsoon onset-based rice planting date

Multiple definitions have been developed to establish the onset of the monsoon season. These definitions vary from local to regional, in which the variables considered to define the onset of the monsoon may be rainfall, wind direction, or other variables associated with atmospheric circulation [32]. Previous studies have used and compared monsoon onset definitions in South Asia and over the Eastern IGP, describing the main features in the regional monsoon timing patterns and variability [33,34,35]. In this work, the local agronomic onset definition of Marteau et al. [36] was used, which was developed with a focus on agricultural implications. This method defines the monsoon onset as the first wet day (1 mm of rain) of one or two consecutive days with daily rainfall at least 20 mm without a 7-days dry spell less than 5 mm of rain during the 20 days from the onset. A post-onset dry spell allows to identify false onsets. This method has been previously used for monsoon timing studies in South Asia and other monsoon regions [32,37]. In this work, the monsoon onset in Bihar was calculated using daily CHIRPS rainfall data for the period 1982 through 2015. Subsequently, the calculated monsoon onset dates were used as rice planting dates, as explained below.

2.4. APSIM gridded crop modeling

The Agricultural Production Systems sIMulator (APSIM) model was used to assess the potential benefit of using the monsoon onset as a rice planting date for climate adaptation strategy. By accounting for soil properties and climate influences, along with management options, APSIM corresponds to a deterministic crop model that has been widely used and calibrated to evaluate the response of crops to management [38], the impacts of climate change and adaptation options for crops [39], or the integrated assessment of yield gaps [40]. APSIM incorporates specific crop modules for rice and wheat simulations [41,42] along with soil water and nutrient balances, among other management options. A good performance simulating rice-wheat systems by APSIM has been reported in multiple studies conducted in South Asia [43]. In this work, APSIM was run using 0.05º × 0.05º spatial resolution input data using the Parallel System for Integrating Impact Models and Sectors (pSIMS; 44), which is designed for high-performance computing gridded simulations.

APSIM was run using parameters for two varieties widely cultivated over the study area (MTU7029 for rice, and PBW343 for wheat), and for which APSIM has been previously calibrated and validated under non-limiting nitrogen and water conditions [38]. In APSIM, rice planting date was set according to the farmers' practice, estimated using NDVI and TIMESAT, and to the monsoon onset date, calculated using the agronomic definition. Likewise, wheat was sown 25 days after rice harvest [45], and irrigation was supplied at the moment when soil water content reached the APSIM threshold for water stress conditions.

2.5. Assessing temperature stress on rice and wheat

The simulated potential yield of rice and wheat for the two rice planting date scenarios were analyzed in terms of the occurrence of temperature stress conditions at the end of the rice (low temperature stress) and wheat (terminal heat stress) growing seasons. The latter was performed through the analysis of the APSIM spikelet sterility factor due to low temperatures in rice (*sf1*), and the exposure to heat stress in wheat (*temp_stress_photo*). *sf1* and *temp_stress_photo* correspond to linear functions of air temperature ranging from 0 to 1, used as multiplicative factors constraining potential yields. In this way, a *sf1* and *temp_stress_photo* factor equals to 1 means no yield reduction due to temperature stress.

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3. Results

3.1. Mean planting and harvest dates of rice and wheat in Bihar

Planting and harvest dates obtained from the two rice planting scenarios are presented. Figure 2 shows both the maps and histograms of mean rice and wheat planting and harvest dates. Figures 2a and 2b show that, in general, the monsoon onset scenario results in earlier planting dates (mean regional DOY= 161) than the farmers' practice (mean regional DOY = 184) in Bihar; the higher differences observed over the eastern part of the state. Similarly, the histogram of Figure 2e shows a higher amplitude in planting dates for the farmers' practice scenario (regional standard deviation of 23 days) compared with the monsoon onset (regional standard deviation of 10 days). On the other hand, it is observed that rice planting dates at monsoon onset concentrate around the average DOY 161 (Figure 2f). The latter immediately suggests that using the monsoon onset as a criterion for the planting date of rice leads to both earlier and also more homogeneous planting dates. For the case of wheat, the map of Figure 2c shows a similar spatial pattern to rice, evidencing the later and more variable dates for the case of the farmers' practice. In this case, later dates are dominant over Southern Bihar and over some areas to the North (areas with lower DOY values representing dates of the following calendar year). The histogram of Figure 2g shows dates starting from around DOY 300 to 80 of the following year. A very different spatial distrution of planting dates is observed for the case of the monsoon onset scenario, with dates much more homogeneous, which concentrate around DOY 320.

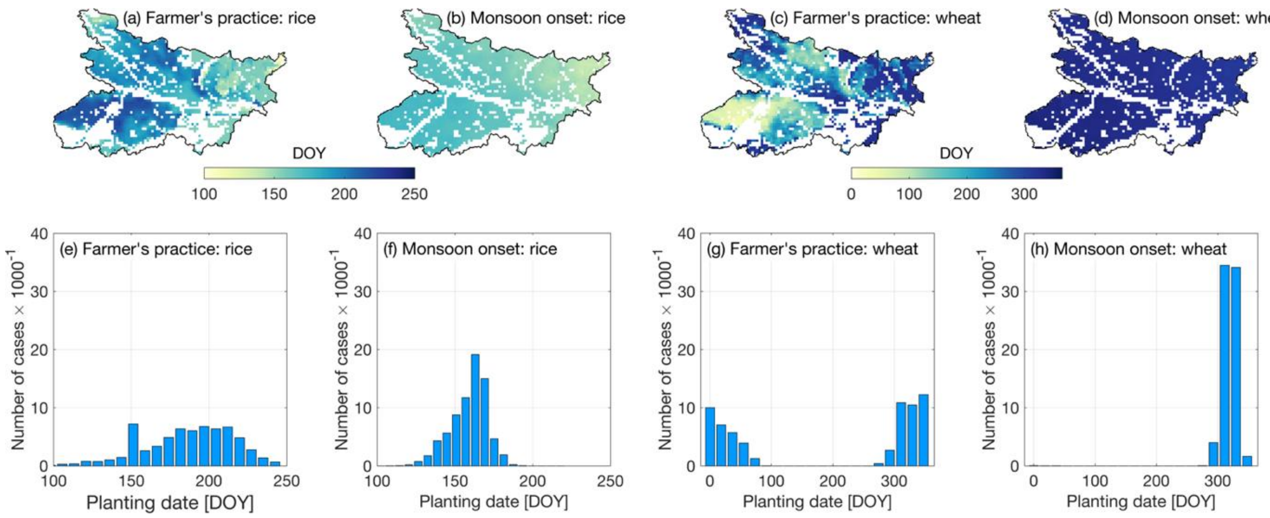

Figure 2. Maps and histograms of interannual (1982-2015) mean planting dates (day of the year, DOY) of rice and wheat for the farmers' practice and monsoon onset rice planting scenarios.

Harvest dates, obtained by APSIM simulations for both rice planting dates scenarios are presented in Figure 3 as maps and spatial histograms of interannual average dates. Following the pattern of planting dates presented previously, the maps of rice harvest dates from monsoon onset scenario leads to relatively earlier but especially more homogeneous dates compared to the farmers' practices. Figures 3b and 3f clearly show the most homogeneous spatial pattern of harvests for the case of rice planting following the monsoon onset. Similarly, the wheat harvest dates for the scenario following the monsoon onset are very spatially homogeneous and are concentrated in earlier dates compared to farmers' practice.

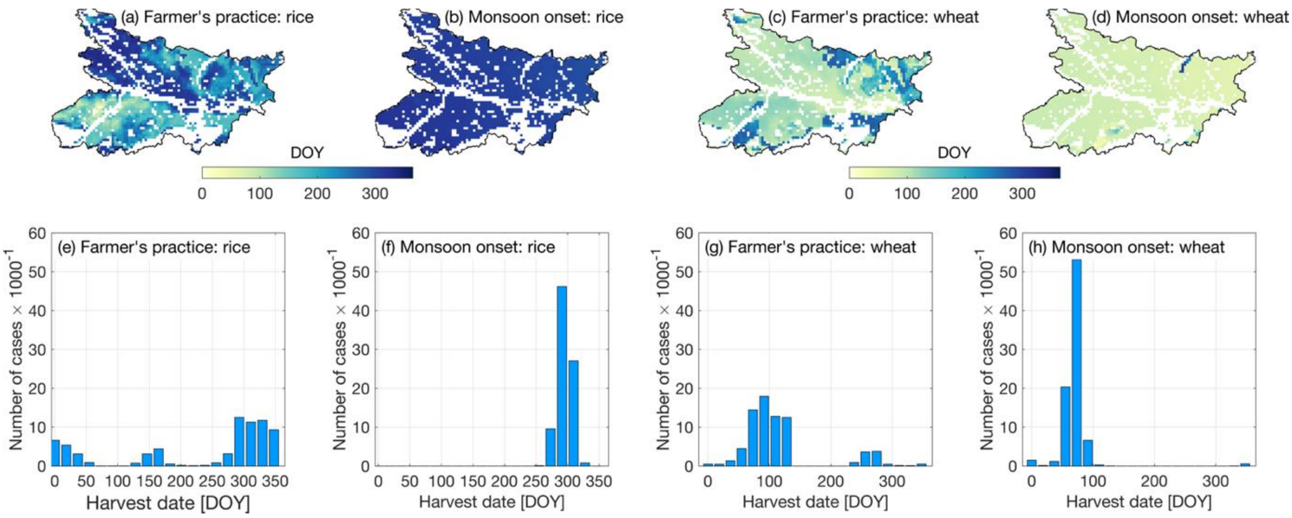

Figure 3. Maps and histograms of interannual (1982-2015) mean harvest dates (day of the year, DOY) of rice and wheat for the farmers' practice and monsoon onset rice planting scenarios.

3.2. The relationship between yields and planting and harvest dates

The simulated mean yields (1982-2015) using both rice planting dates scenarios are presented in Figure 4. The farmers' practice scenario generates yields that are more spatially variable than for the monsoon onset scenario, with the Southwestern areas and parts of the North showing lower potential yields (Figure 4a). The latter results in a bimodal distribution of yields that concentrates around 2,000 and 7,000 kg/ha (Figure 4e). On the other hand, the impact of using the onset of the rainy season as a criterion for rice planting generates higher yields throughout the state of Bihar, showing more spatially homogeneous yields concentrating around 7,000 kg/ha (Figure 4b and 4f). According to Figure 4a and 4b, the higher positive yield change is generated over areas of lower yields (around 2,000 kg/ha), suggesting that higher benefits from earlier rice planting would be obtained over areas of lower yields. Similarly, wheat yields for the case of farmers' practices show a similar spatial distribution to that of rice (Figure 4c). In this case, the planting of rice at monsoon onset again generates a positive impact on wheat yields over low yield areas, which concentrate around 4,000 kg/ha.

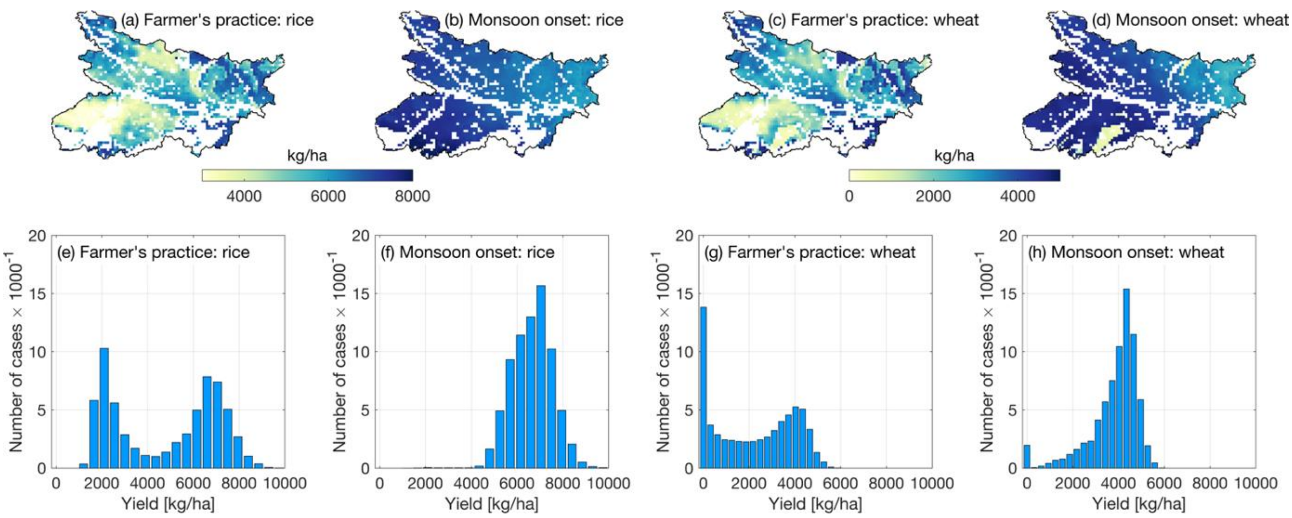

Figure 4. Maps and histograms of interannual (1982-2015) mean yields of rice and wheat for the farmers' practice and monsoon onset rice planting scenarios.

While increasing yields is a primary goal of most crop management strategies, improving yield stability is also important, especially in the context of climate change [46].

The interannual standard deviation of rice and wheat yields was calculated as an indicator of yield stability, which are presented in maps of Figure 5. It is clear the higher spatio-temporal yield variability in both rice and wheat for the case of the farmers' practice dates for rice planting. Large areas of Bihar show relatively unstable yields for the case of the farmers' practice planting dates (Figures 5a and 5c), areas that also average lower yields (Figure 4). On the other hand, the simulated yields for the case of planting at monsoon onset are observed to be temporally stable, with some areas of relatively less stability in the case of wheat (Figure 5d).

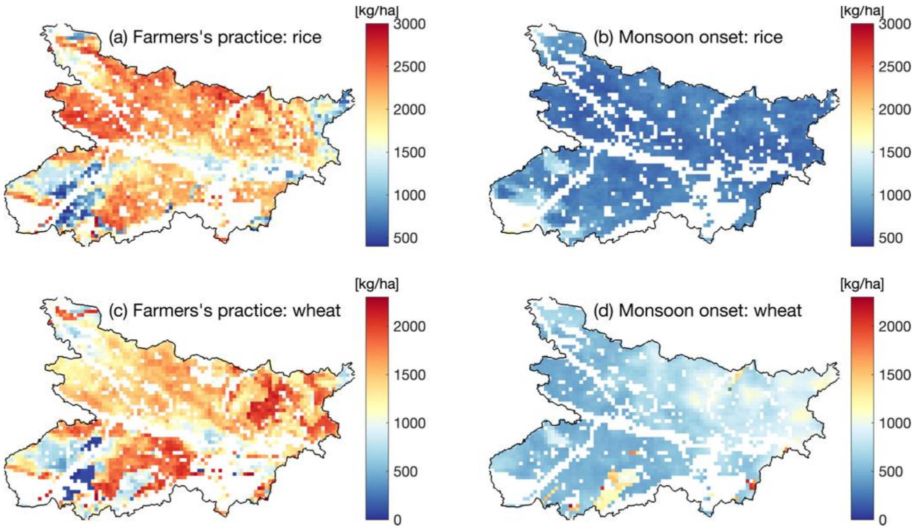

Figure 5. Maps of interannual variability (standard deviation) of rice and wheat yields for the farmers' practice and monsoon onset rice planting scenarios.

3.3. Planting dates and temperature stress factors: interannual patterns

In order to explore the effect of the planting date of rice and therefore of wheat on the incidence of thermal stress, the values of the APSIM stress factors (*sf1* for rice and *temp_stress_photo* for wheat) were compared for both planting scenarios. Results of Figure 6, where the time series of stress factors (1982-2015) for rice and wheat and for the two planting date scenarios are displayed, show that simulated potential yields using the farmers' practices date experience higher yield restrictions associated with temperature stresses, especially for the case of wheat (Figure 6b). The latter suggests a greater relative relevance of stress associated with terminal heat on wheat than low temperatures on rice. Figure 6a clearly shows values closer to unity and lower interannual variability in the case of *sf1* obtained using the monsoon onset (mean *sf1* = 0.98; standard deviation *sf1* = 0.01) compared with the farmers' practice (mean *sf1* = 0.87; standard deviation *sf1* = 0.05). For the case of wheat, the differences between both rice planting scenarios are more evident (Figure 6b). Again, the rice planting scenario with the onset of the rainy season shows values closer to 1 (mean *temp_stress_photo* = 0.88), in addition to much lower interannual variability (standard deviation *temp_stress_photo* = 0.03), compared with the farmers' practice (mean *temp_stress_photo* = 0.66; standard deviation *sf1* = 0.1). These results are indicative of a pattern of higher stability in attainable rice and wheat yields associated with the reduction in the temperature-stress related constraining factors, suggesting that planting rice earlier at monsoon onset could result in a net benefit in terms of rice and wheat.

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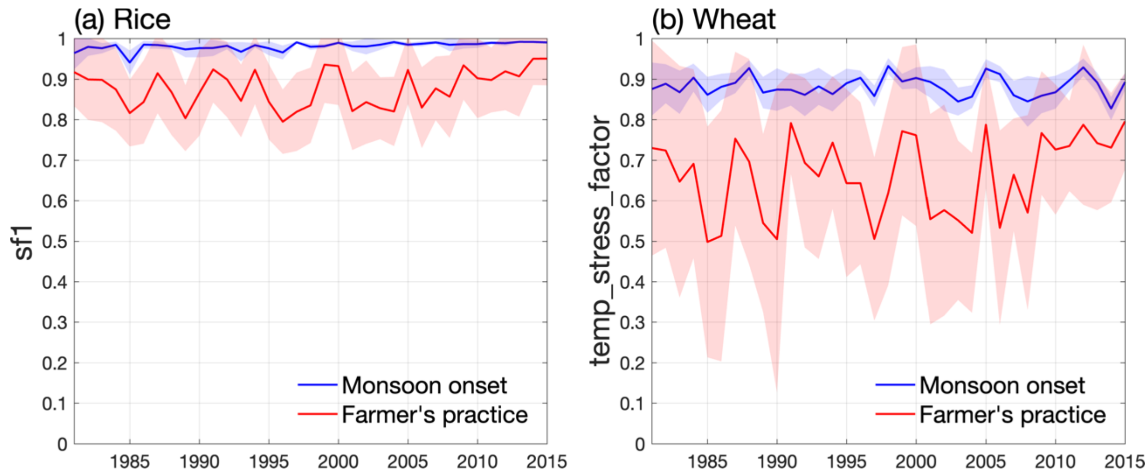

Figure 6. Time series of mean (solid lines) and standard deviation (shaded area) temperature stress factors for rice (*sf1*) and wheat (*temp_stress_photo*) for the farmers' practice and monsoon onset rice planting scenarios.

A composite analysis was performed based on the comparison between the years of lowest and highest yields, represented by the 15th and 85th percentiles for every model grid, respectively. Figure 7 shows the maps of both average yields and values of the stress factor *sf1* for rice planting date strategy. Generally, maps of simulated yields (Figures 7a and 7b) for the farmers' practice are in agreement with those of *sf1* (Figures 7e and 7f), which show that the areas of higher/lower yields agree with those of higher/lower values of *sf1*, suggesting a direct relationship of the effect of thermal stress on rice yields. On the contrary, the maps of high and low relative rice yields for the case of planting at monsoon onset show much more homogeneous spatial distribution of yields, and no correspondence between the lower yields of Figure 7c with lower values of *sf1* in Figure 7g. The latter suggests that factors other than the effect of stress due to low temperatures would explain the lower yields achieved during specific years.

The case of simulated wheat yields shows similar results to the case of rice (Figure 8). In the composites of farmers practices (Figure 8a), higher relative yields are observed in the areas further north of Bihar, which in general have *temp_stress_photo* values closer to 1 (Figure 8e). Similar to the case of rice, the spatial patterns of both yield and *temp_stress_photo* for the composite of monsoon onset planting (both relatively low and high wheat yields) do not show a clear association between the spatial distribution of wheat yields and the values of *temp_stress_photo* (Figures 8c and 8g, and Figures 8d and 8h), being the values of *temp_stress_photo* very similar for both composites (Figure 8g and 8h), which would be indicative of a lower incidence of terminal heat stress on wheat when rice is planted earlier in the season together with the onset of the rainy season.

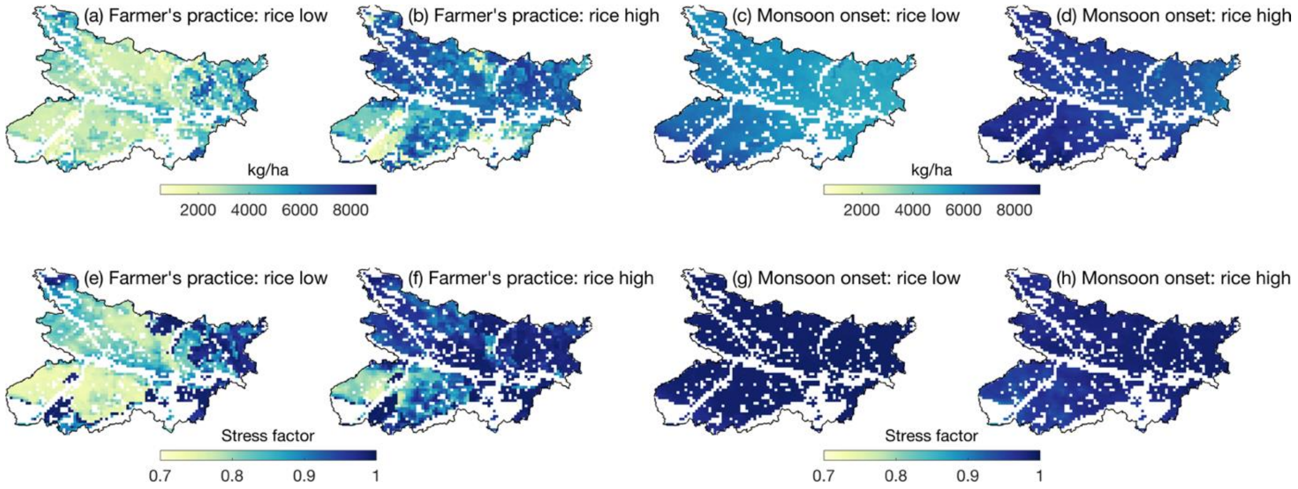

Figure 7. Maps of (a)-(d) mean yields and (e)-(h) temperature stress factors (SF) for rice (*sf1*) of the composites of low (percentile 15th) and high (percentile 85th) yields for farmers' practice and monsoon onset rice planting scenarios.

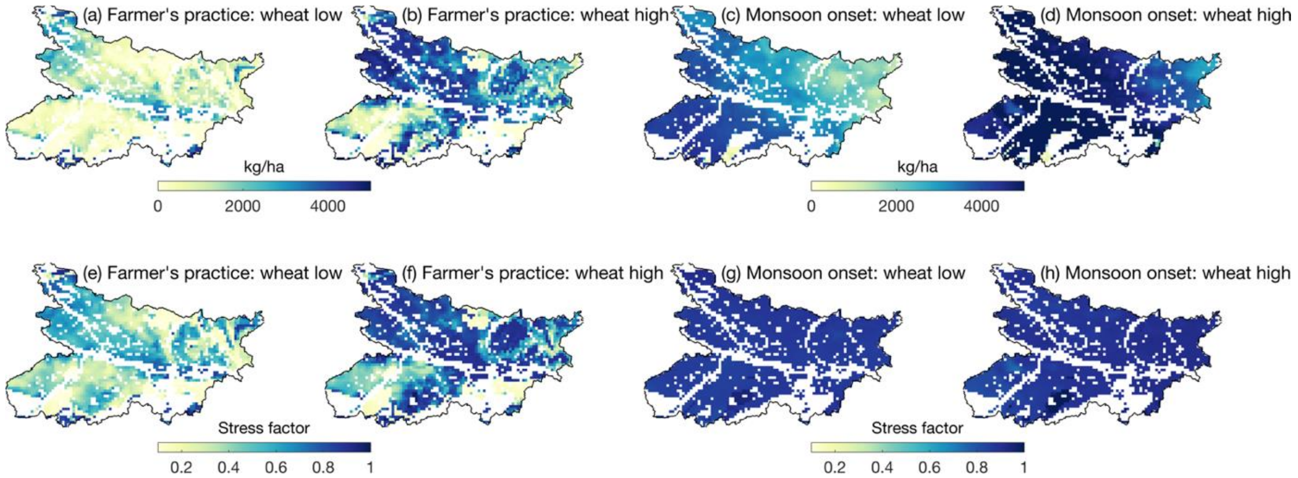

Figure 8. Maps of (a)-(d) mean yields and (e)-(h) temperature stress factors (SF) for wheat (*temp_stress_photo*) of the composites of low (percentile 15th) and high (percentile 85th) yields for farmers' practice and monsoon onset rice planting scenarios.

4. Discussion

The main goal of this study is to assess the potential benefit of planting rice at the onset of the rainy season in relation to current farmers' practices in terms of rice-wheat system yields achieved and their stability over time, with emphasis on the incidence of thermal stresses. The foregoing under the hypothesis that an earlier planting of rice in relation to current farmers' practices and timely in terms of the use of rainwater allows to avoid the exposure of both rice to low temperatures, and subsequent wheat to terminal heat stress. The literature shows that the incidence of thermal stress on rice and wheat in Bihar can generate significant impacts on yields, which suggests that advances in adaptation strategies are necessary.

The results shows that planting dates using monsoon onset are around 20 days earlier than current farmers' practice, estimated using satellite information. Consequently, simulations presented and discussed suggest that the use of the monsoon onset as a criterion for rice planting date in Bihar would improve rice-wheat yields and its stability initially by reducing the exposure of both rice to low temperature stress and wheat the terminal heat stress. Although further work is needed in order to implement an operational

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system allowing farmers to use the monsoon onset as an option for planting rice, the results of this work seem to indicate that it would be worth exploring the options available for a potential future implementation. In this sense, the current development of sub-seasonal and seasonal forecasts at multiple lead times [47] would allow the generation of actionable information for decision-making by farmers. In this way, the meteorological departments could provide the necessary information for the development of targeted climate services in Bihar and other areas.

The modeling results show that the incidence of stress associated with low temperatures in rice and high temperatures in wheat may be relevant in Bihar. Considering current climate change and warming projections for the region, it is likely that the incidence and severity of terminal heat stress on wheat will increase in the future [17]. In this context, adaptation strategies that are relatively easy to implement, such as the one presented in this work, could become important for decision-makers.

Although the results show clear differences in planting dates, rice-wheat yields and incidence of thermal stress, they have to be interpreted with caution since they were generated from a modeling work using multiple data sources with their own limitations and uncertainties. First, estimated farmers' practice planting date can be uncertain given the use of the TIMESAT algorithm which works by smoothing the NDVI signal, using also a prescribed percentage of the signal amplitude to identify the onset of the season, in this case 20%. Beyond the uncertainties associated, for example, with the quality of satellite products, a sensitivity analysis to this signal amplitude factor should be performed to better understand the results. Additionally, several methods have been developed to define the monsoon onset [32]. In this work we have selected the agronomic onset definition since it was generated for agricultural applications; but clearly a more complete comparison of monsoon onset definitions should be carried out. Despite all the limitations, the model results still provide insights about the potential use of the monsoon onset as a criterion for rice planting dates over a region of high vulnerability to environmental hazards, the production of actionable climate services, and the potential impact of the use of climate forecasts and predictions in decision making, provided that effective delivery methods are also developed in order to translate climate information into practices for adaptation and mitigation.

5. Conclusions

Multiple studies have reported the adverse effects of low temperatures on rice and terminal heat on wheat over northern India. Despite the fact that the foregoing is widely known, the development of adaptation strategies at the regional level that are aligned with the current efforts in adaptation to climate change is a pending task. In this sense, this study analyzed the potential use of the monsoon onset for planting date of rice and its impacts on rice-wheat yields and the incidence of thermal stresses as a adaptation strategy on rice-wheat systems in Bihar. In addition, the strategy evaluated in this study considers only climate information for decision making. The results show that important regional differences in terms of planting dates and attainable rice-wheat yields for both rice planting scenarios across Bihar. The spatial differences in the potential benefit on yields of using the monsoon onset as a rice planting strategy could help focusing efforts in order to develop and deliver actionable climate services to mitigate the impact of climate hazards on rice-wheat systems of Bihar, and to adapt farmers to projected climate change. Following the approach used in this work, future efforts should focus, for example, on analyzing the potential benefit of shifting the planting date of rice on rice-wheat systems of Bihar using climate change scenarios. Although projections are uncertain as to the likely changes in the rainfall pattern across South Asia, the generalized warming suggests that an earlier wheat sowing date could help mitigate the impact of climatic shocks that represent the high temperatures during the terminal stage of wheat growth.

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