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Spatiotemporal pattern of the dynamics in area, production, and yield of *Aus* rice in Bangladesh and its response to droughts from 1980 to 2018

KHONDAKAR Arifuzzaman[1,2,3], DONG Jinwei[1,2], *LI Zhichao[1], DENG Xiangzheng[1], SINGHA Mrinal[1], RAHMAN Md. Mizanur[4], JIN Zhenong[5], WANG Shaoqiang[1], ZHEN Lin[2,6], XIAO Xiangming[7]

1. Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
2. University of Chinese Academy of Sciences, Beijing 100094, China;
3. Department of Geography and Environment, Pabna University of Science and Technology, Pabna 6600, Bangladesh;
4. Deputy Director (Monitoring), Field Services Wing, Department of Agricultural Extension, Ministry of Agriculture, Bangladesh;
5. Department of Bioproducts and Biosystems Engineering, University of Minnesota-Twin Cities, Saint Paul, MN, USA;
6. Institute of Geographic Sciences and Natural Resources Research, CAS, Beijing 100101, China;
7. Department of Microbiology and Plant Biology, University of Oklahoma, Norman OK 73019, USA

Abstract: Bangladesh is one of the most vulnerable countries to natural disasters such as droughts in the world. The pre-monsoon *Aus* rice in Bangladesh depends on rainfall and is threatened by increasing droughts. However, limited information on the changes in *Aus* rice as well as droughts hamper our understanding of the country's agricultural resilience and adaption to droughts. Here, we collected all the official statistical data of *Aus* rice at the district level from 1980 to 2018, and examined the interannual variations of area, yield, and production. The results showed both area and production of *Aus* rice decreased significantly (61.58×10^3 ha yr^{-1} and $17.21\ \times10^3$ M. tons yr^{-1}, respectively), while yield increased significantly (0.03 M. tons ha^{-1} yr^{-1}). We also found a significantly increasing trend of droughts in 88% of area based on the Palmer Drought Severity Index (PDSI) data, especially in those rainfed agricultural areas. Moreover, we found significant positive correlations between PDSI and *Aus* rice area (production) in 33 (25) out of 64 districts. There is hardly a relationship between PDSI and yield, likely due to the improved management and increasing irrigated areas. Implementing continuous drought monitoring, combined irrigation (surface and groundwater) systems, and conservation and precision agriculture are highly recommended in these drought-prone districts to ensure food security in Bangladesh.

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Author: Khondakar Arifuzzaman (1984–), PhD Candidate, specialized in geographic information system.
E-mail: arifuzzaman@igsnrr.ac.cn
***Corresponding author:** Li Zhichao (1986–), PhD, specialized in geographic information system. E-mail: lizc@igsnrr.ac.cn

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1 Introduction

According to the Food and Agriculture Organization (FAO), agricultural land comprises 71% of the total land area in Bangladesh and 41% of people adopted agriculture as their employment (FAO, 2019). The Global Information and Early Warning System (GIEWS) on food and agriculture alerted Bangladesh experiencing severe localized food insecurity in 2019. It will be a challenge to feed additional 30 million people in the next 30 years for Bangladesh (FAO, 2020) and simultaneously achieve the United Nations Sustainable Development Goals (SDGs) 2 and 13 with the potential threat of climate variability and natural disasters like droughts and floods. Moreover, paddy rice imports are abruptly increasing in Bangladesh, especially since 1990 (Figure S1). Unfortunately, there has been hardly any knowledge of the spatial and temporal pattern of the country's current status and history of food production and security.

Rice is the staple grain in Bangladesh and unusually includes three seasons: *Aus* (April-July), *Aman* (August-November), and *Boro* (December-March) (Amin *et al.*, 2015; Shelley *et al.*, 2016). Drought is a severe problem for agricultural production in Bangladesh, and drought-related damages are intense (Shahid, 2008; Shahid and Behrawan, 2008; Ruane *et al.*, 2013; Uddin *et al.*, 2019). Specifically, *Aus* rice is more affected by droughts as it is a pre-monsoon crop and mostly depends on rainwater (Shahid, 2010; Shelley *et al.*, 2016). Moreover, *Aman* rice is the monsoon-season rainfed rice, which could also be affected by precipitation change in summer. A previous study estimated that precipitation change would decline the *Aus* and *Aman* rice yield by 1%–10% and 1%–2%, respectively (Islam, 2015). *Boro* rice mainly relies on groundwater irrigation in Bangladesh, and the direct impacts of droughts on *Boro* rice are limited. Compared with *Aman* and *Boro*, *Aus* season rice is the most vulnerable to droughts (Islam, 2004). However, there are limited efforts on analyzing the long-term impacts of droughts on *Aus* rice in Bangladesh to date.

Climatic variability has made Bangladesh prone to natural hazards such as droughts, and previous studies have identified the spatial and temporal patterns of droughts using various data sources, periods, and methods. For example, droughts have affected about 47% of the country and 53% of the total population in Bangladesh (Selvaraju and Baas, 2007). Frequent droughts occur mostly in the northwestern districts of Bangladesh (Shahid, 2008). Moreover, drought frequency has increased in the western region of Bangladesh, and it is expected to increase at a higher rate in the future (Shahid and Behrawan, 2008). A recent study found that drought intensity is higher in western Bangladesh in terms of duration and frequency (recurrence epoch less than 25 years), while the severity of droughts is higher in eastern and southern Bangladesh (return period exceeds 25 years) (Mortuza *et al.*, 2019). However, it is still unclear whether droughts have been increasing in the whole of Bangladesh, and how the change in droughts affects the *Aus* rice production.

There are different drought indices used in previous studies, such as the Standardized Precipitation Index (SPI) (McKee *et al.*, 1993), Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano *et al.*, 2010), and Palmer Drought Severity Index (PDSI) (Palmer, 1965). Among them, PDSI was developed primarily to detect agricultural drought considering the soil moisture content and crop failure phenomenon for a specific time period

(Mishra and Singh, 2010). It was developed by integrating monthly temperature and precipitation data with a water-holding capacity of soils calculated by considering moisture received (precipitation) and potential loss of moisture due to temperature influences; soil water storage statistics are integrated by default (Svoboda and Fuchs, 2016). Such an index has been used for measuring the agricultural drought in different countries of the world, such as Argentina (Scian and Donnari, 1997; Scian, 2004), China (Zhai *et al.*, 2010; Huang *et al.*, 2015; Qin *et al.*, 2015; Gong *et al.*, 2016; Wang *et al.*, 2016; Zhang *et al.*, 2019; Guo *et al.*, 2021), and the United States of America (Guttman *et al.*, 1992; Choi *et al.*, 2013; Tian *et al.*, 2018). PDSI was reported to perform well in the Georgia region of the USA (Choi *et al.*, 2013), and it showed the better capability to detect regional differences in drought frequency in China compared to SPI (Zhai *et al.*, 2010). However, its application in South Asia has been rarely reported.

To date, no detailed study has yet been conducted to elucidate the causes of the changes in area, production, and yield of paddy rice at the sub-national level in Bangladesh. Analyzing recent impacts of climate trends and associated aftermath on food availability will assist in comprehending potential future influences of the likely changed climate. Besides, detecting the impact of near real-time climate change on crops and regions will aid in analyzing current initiatives and pave the way towards adaptation by implementing necessary measures (Lobell *et al.*, 2011).

In this context, this study aims to draw an entire picture of the spatial and temporal pattern of the area, production, and yield of *Aus* rice in Bangladesh during 1980–2018, and explore the potential effects of droughts on *Aus* rice. Specifically, we aim to answer three questions: 1) what are the spatial and temporal patterns of the area, production, and yield of *Aus* rice in Bangladesh during 1980–2018? 2) What is the trend of pre-monsoon season droughts in Bangladesh? and 3) whether the increasing droughts have affected the *Aus* rice in Bangladesh? Such a picture of *Aus* rice and its response to the droughts would shed light on sustainable agriculture development and achieving the food security target in Bangladesh.

2 Materials and methods

2.1 Study area

Bangladesh is a South Asian country spanning between 20°34'–26°38'N and 88°01'–92°41'E (Figure 1), which has a total area of 147,570 km^2 and consists of 64 districts. Approximately half of the surface area of Bangladesh is 10 m below sea level. Hills are confined to the eastern and southern regions of the Sylhet, and southeast region of the country in Chittagong district (Figure 1). Bangladesh has a sub-tropical climate dominated by the monsoon. There are three distinct seasons in Bangladesh, including the hot pre-monsoon summer (March-May), rainy monsoon (June-October), and cold winter (November-February) (Islam, 2004). The average maximum and minimum temperatures in summer are 34°C and 21°C, respectively, and annual rainfall ranges from 1194 mm to 3454 mm. Moreover, according to the Bangladesh Bureau of Statistics (BBS) and the Department of Agricultural Extension (DAE), the relative proportion of the area of *Aus* rice lessened from 30% to 10% during 1971–2018, and the production of *Aus* rice reduced 12% in 2018 compared to that in 1980.

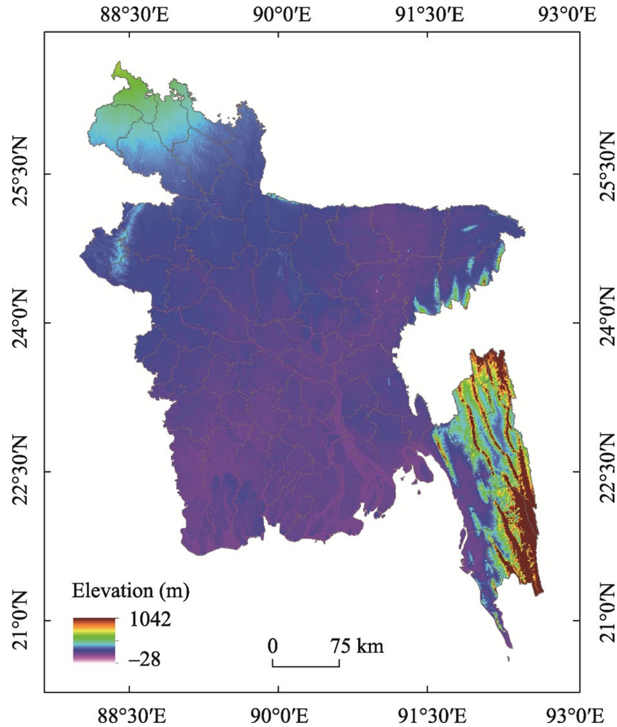

Figure 1 The elevation map of the study area (Bangladesh, South Asia)

2.2 Data

2.2.1 Area, yield, and production of *Aus* rice

The data of the *Aus* rice area and production (milled-rice equivalent) from 1980 to 2018 were derived from the official statistical data of DAE, BBS, and Bangladesh Rice Research Institute (BRRI). DAE and BBS collect the rice statistics from separate field surveys, which were then adjusted and provided to BRRI for publication. Data preprocessing was done due to the adjustment of administrative divisions in the past four decades. All the acreage data were converted from acres to hectares (ha), and production data were changed from Metric tons (M. tons) per acre to M. tons per ha. *Aus* area and production data were available for 23 bigger districts from 1980 to 2005, and data from 2006 to 2018 were available for all the current 64 districts. Therefore, area and production data of the earlier timespan were split into current administrative units based on their total proportional area in the mother-administrative units. For instance, if the previous bigger district, X was split into new districts x_1, x_2, …, and x_i, then the cultivation area or production of smaller district x was calculated using the following equations (1) and (2):

$$A_i = \left(\frac{x_i}{\sum_1^n x_i} \right) \times A \tag{1}$$

$$P_i = \left(\frac{x_i}{\sum_1^n x_i} \right) \times P \tag{2}$$

where A and P represent the acreage and production of mother district, respectively, A_i and P_i represent the acreage and production of the new district i, respectively, and x_i, represents the total area of new district i.

Afterward, the yield of paddy rice was estimated by dividing the production by the allocated acreage that was computed using the following equation (3):

$$Y_t \cong \frac{Q_t}{A_t} \tag{3}$$

where Y_t, Q_t and A_t represent the yield, production and allocated acreage of paddy rice, respectively.

To isolate the effects of non-climate factors, such as variance in yield due to the variety of paddy rice and management practices (technical advancement), fertility, insects and diseases, the paddy rice yield time series was de-trended by applying the following equation (4) (Lobell *et al*., 2011):

$$Y_i = Y_{oi} - Y_{ti} \tag{4}$$

where Y_i is the de-trended crop yield for location i, Y_{oi} is the observed crop yield for location i, and Y_{ti} is the trend crop yield for location i.

De-trended crop yield was then standardized (Du *et al*., 2013) by using the following equation (5):

$$St.Y_i = \frac{Y_i - \overline{Y}}{\delta_Y} \tag{5}$$

where Y_i, $\overline{Y}$ and δ_Y represent the de-trended crop yield, mean value of de-trended crop yield, and the standard deviation of de-trended crop yield, respectively.

2.2.2 PDSI data

We used the PDSI as a proxy of agricultural drought. Palmer proposed the PDSI as a drought index based on the meteorological anomaly with an initiative to understand the likelihood of drought occurrence and their course that makes it possible to space-time comparison of droughts. The underlying principle is that the departure of moisture from normal condition could be enumerated by subtracting computed normal precipitation from actual precipitation. Proper weighting of this moisture deviation generates an index that could be used for spatio-temporal comparison (Palmer, 1965). The PDSI proposed by Palmer is computed as follows:

$$X_j = 0.897 X_{j-1} + \frac{Z_j}{3} \tag{6}$$

$$Z = dK \tag{7}$$

where X_j and Z_j represent the PDSI and moisture anomaly for the j-th month, respectively. K is the climatic characteristics for weighting the moisture deviation. d denotes the deviation from normal precipitation level for a specific time and space, which is calculated based on various input parameters, including the evapotranspiration, recharge, runoff, loss, potential evapotranspiration, potential runoff, potential recharge, and potential loss (see more detailed information in Palmer (1965)).

Palmer used the Thornthwaite method to estimate potential evapotranspiration that is commonly used for calculating PDSI. However, in this study, we used the PDSI derived from TerraClimate dataset in the Google Earth Engine (GEE) platform (Abatzoglou *et al.*, 2018). In fact, TerraClimate dataset was developed through the integration of the WorldClim dataset (high spatial resolution), CRU Ts4.0 data (coarser spatial resolution, time-varying), and the Japanese 55-year Reanalysis (JRA55). Then, by incorporating reference evapotranspiration, temperature, precipitation, and interpolated plant extractable soil water capacity at 0.5° grid, TerraClimate produced the monthly surface water balance datasets based on a modified Thornthwaite-Mather method, as it was less sensitive to temperature (Tian *et al.*, 2018).

2.2.3 Irrigation and rainfall data

The irrigation-based crop map was obtained from Global Food Security Support Analysis Data (GFSAD). We used the data of the irrigated area and net cultivable area of Bangladesh from BRRI. We also used the data of irrigation area percentage (as a percentage of total area), areas irrigated with groundwater and surface water (as a percentage of total equipped area) from FAO, respectively. The mean monthly and annual rainfall data during 1980–2018 were obtained from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS).

2.3 Methods

2.3.1 Computation and validation of PDSI

We first validated the PDSI by correlating it with soil moisture derived from the TerraClimate dataset for each of the new districts in Bangladesh. Most districts had the high correlation between them (Table S1), and a mean value of correlation coefficient for all districts is 0.62. In this case, we extracted the district level mean PDSI of *Aus* season (April-July) of each year during 1980–2018 using the zonal statistics in GEE platform, which was further used for spatio-temporal comparison, correlation, and regression analysis with the district-level area, production, and yield of *Aus* rice. Here, different droughts levels were defined based on PDSI values, according to the criteria listed in Table 1 (Alley, 1984).

Table 1 Different drought levels based on PDSI

Different categories	Non-drought	Incipient drought	Mild drought	Moderate drought	Severe drought	Extreme drought
Scale values	⩾ –0.49	–0.50 to –0.99	–1.00 to –1.99	–2.00 to –2.99	–3.00 to –3.99	⩽ –4

2.3.2 Trends of acreage, production, and yield of *Aus* rice

To understand the temporal trends of *Aus* rice, the linear regression analysis (Bluman, 2018) of the acreage, production, yield, and PDSI was computed at both country-level and district-level as follows:

$$y = ax + b \tag{8}$$

where a symbolizes the slope of the linear regression line and b denotes the intercept.

2.3.3 Relationship between *Aus* rice acreage, production, and yield and PDSI

To investigate the impact of droughts on *Aus* rice, the Pearson correlation (Bluman, 2018, Pearson, 1895) between acreage, production, and yield of *Aus* rice and PDSI was computed as follows:

$$r = \frac{n\left(\sum xy\right) - \sum x \sum y}{\sqrt{n\left(\sum x^2\right) - \left(\sum x\right)^{2?}}\sqrt{n\left(\sum y^2\right) - \left(\sum y\right)^2}} \tag{9}$$

where x is the acreage, production, or yield of *Aus* rice, y is the PDSI, r is the Pearson correlation coefficient, and n is the number of samples (years).

We compared these maps and graphs with the drought trend map to understand the influencing factors of droughts and its impact on *Aus* rice, as the inconsistency of rainfall is described as the most significant natural factor for agricultural production (Shahid, 2010). Lastly, linear regressions of standardized PDSI and acreage, production, and yield were conducted to detect the drought influence on *Aus* rice.

3 Results

3.1 Changes in area, yield, and production of Aus rice at country-level

The total area of *Aus* rice has gradually decreased from 3.1 million ha in 1980 to around 1.1 million ha in 2018, with a rate of 61.6 thousand ha per year (Figure 2a). Around 65% reduction of cultivation area in the last four decades. Specifically, a sharp downward oscillation is observed from 1980 to 1993 when the area saw almost 50% reduction. Then, after a sudden 73% drop in 1995, it displays a little rise in 1996. Afterward, it shows moderate descending drift of area until 2006 which quantifies to around 35% reduction compared to that of 1996. Next, it has moved forward almost straightly until 2016, following a little rise till 2018. In terms of production, it has diminished at a rate of 17 thousand M. tons per year (Figure 2b), with a decreasing trend from 1980 to 2007, and a moderate upward drift afterward. The maximum fall is observed in 1987 and 1995, and the highest production is observed from 1980–1981, nearly 3200 thousand M. tons. In recent years, an increase of *Aus* rice production is observed. In terms of yield, a gradual modest upward trend is observed from 1980 to 2018 with an average rate of 0.03 M. tons per ha (Figure 2c), except for a swift fall in 1987.

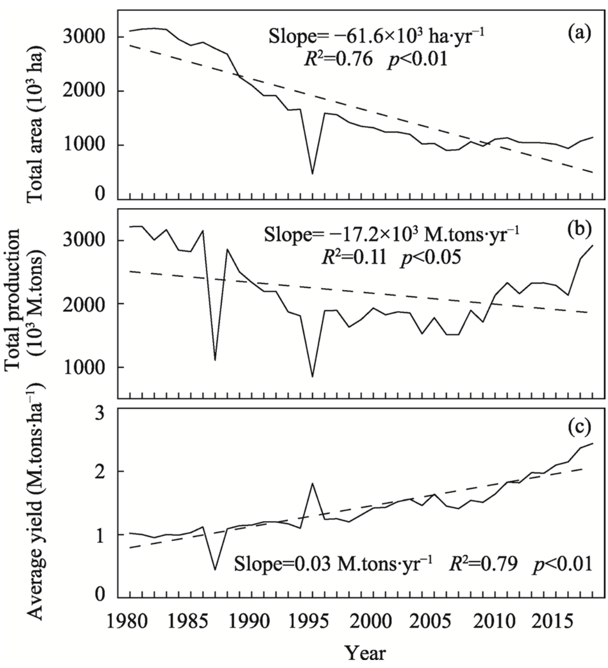

Figure 2 Interannual variations and trends of *Aus* rice total area (a), total production (b), and average yield (c) in Bangladesh from 1980 to 2018

3.2 Changes in area, production, and yield of Aus rice at district-level

According to the multi-year mean of *Aus* rice area of the 64 districts (Figure 3a), a statistically significant reduction of acreage (at 5% confidence interval) has been observed in 55 of the total 64 districts (Figure 3d). The area declined at a rate of greater than 1000 ha yr^{-1} in most of the central and upper-central districts, and with 2000 ha yr^{-1} in several central and

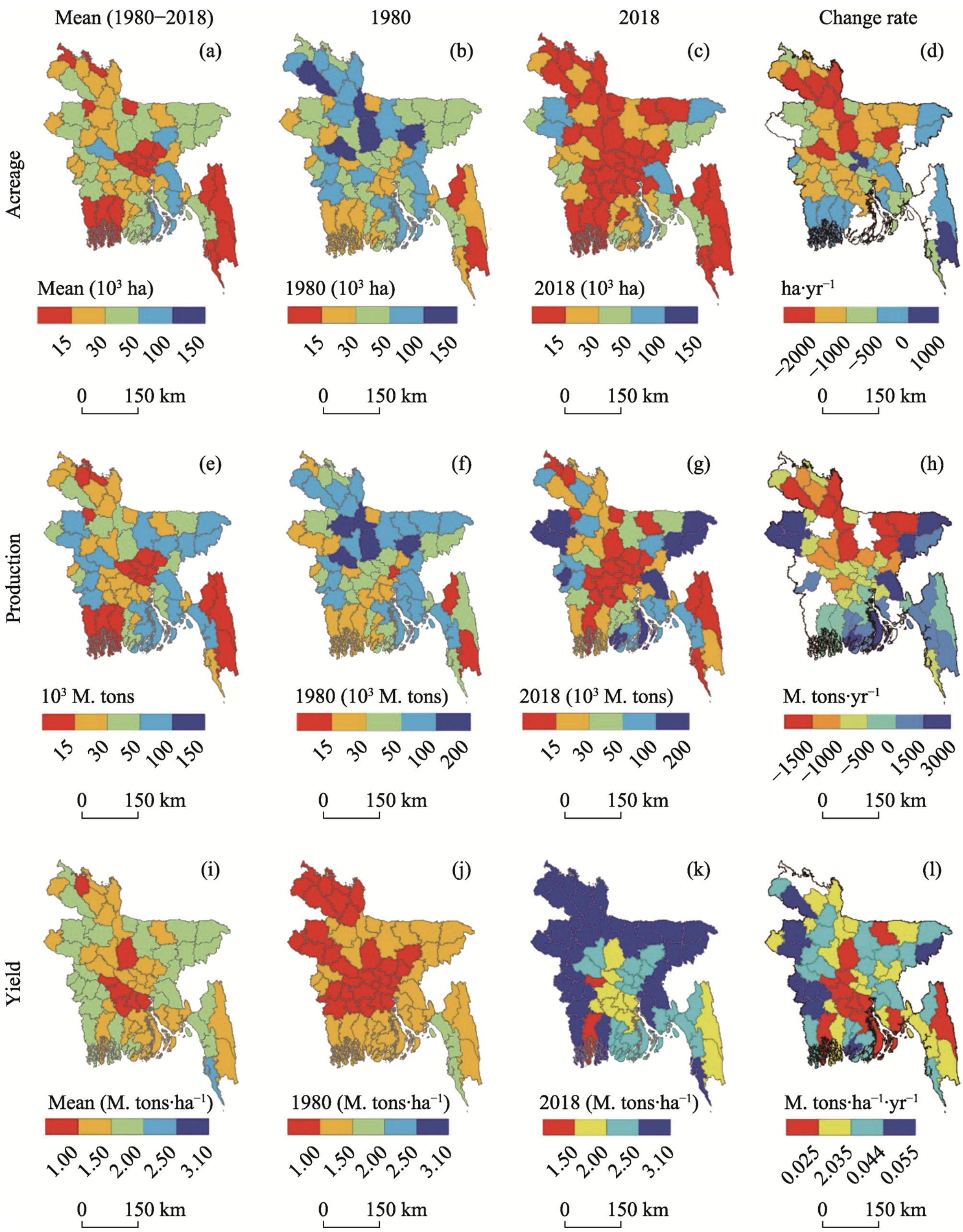

Figure 3 The mean (1980–2018), baseline (1980), recent (2018), and trends of *Aus* rice acreage, production, and yield at the district level during 1980–2018. The white color in column 4 represents the districts with non-significant trend of change rate

majority of the northern districts. In terms of production, a significant reduction was observed in 44 districts (Figure 3h). However, a noticeable increase in production was observed in the northeastern, northwestern, southeastern, and southern regions. In terms of yield, 63 districts showed a statistically significant upward trend in yield at a 5% confidence interval (Figure 3l). However, the low increase rate of yield (0.02 M. tons ha^{-1} yr^{-1}) was observed in the central regions of Bangladesh (Figure 3l). The comparison between 1980 and 2018 reveals that the yield gain has been achieved in the northern and northwestern regions.

3.3 Change of PDSI at both country-level and district-level

The country-level average PDSI in *Aus* season (April-July) reveals a significant increasing trend of droughts in Bangladesh in the pre-monsoon season during 1980–2018 (Figure 4). Linear regression reveals that PDSI has decreased (increase of droughts) at a rate of 0.07 unit/year at 5% confidence interval.

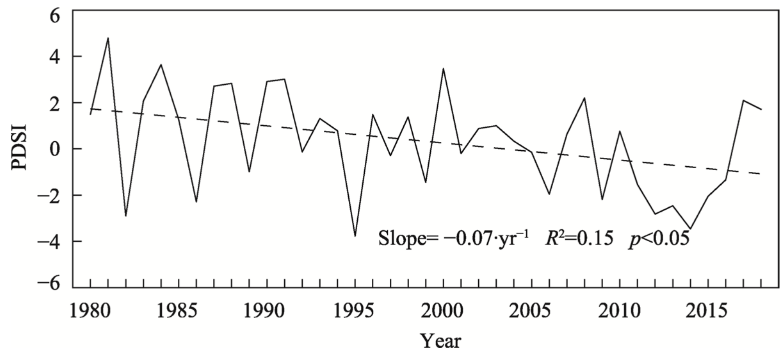

Figure 4 Interannual variation of PDSI in Bangladesh in the pre-monsoon season during 1980–2018. The downward linear trend represents the decreasing trend of PDSI that ascertains the increasing drought in Bangladesh

The district-level mean (1980–2018), baseline (1980), recent (2018), and trend of pre-monsoon drought at 5% confidence interval are provided in Figure 5. The higher increasing rates of drought were observed in the northeastern, central, and southern districts that varied from 0.076 to 0.096 unit/*Aus* season/annum. In the central-surrounding and southwestern regions, drought increased at a rate of 0.071 to 0.075 unit/ *Aus* season/annum. However, no significant trend of droughts was observed in the northern and other three districts (Figure 5d).

3.4 Effects of droughts on Aus rice

The *Aus* rice area presented significant positive correlation with PDSI in 35 districts (Figure 6a). That is, the PDSI decreased (the drought increased), and the acreage of *Aus* rice decreased simultaneously. The pre-monsoon drought was prevalent in these districts where farmers could not sow the seed of *Aus* rice in the field. That eventually declined the total production. The production of *Aus* rice has demonstrated significant correlation with PDSI in 25 districts (Figure 6b). Among them, a significant positive correlation was found in 19 districts, with *p*-values varying from 0.004 to 0.08. Moreover, the significant negative relationships were observed in 6 districts, with *p*-values varying from 0.01 to 0.09. Those districts

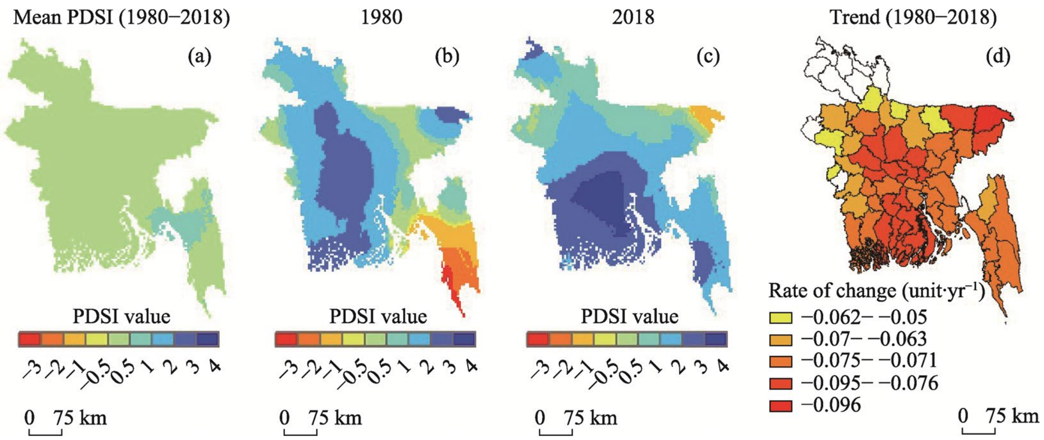

Figure 5 The district-level mean, baseline (1980), recent (2018), and change rate (1980–2018) of drought severity in the pre-monsoon season in Bangladesh during 1980–2018. The white color represents the districts with non-significant trend of change rate

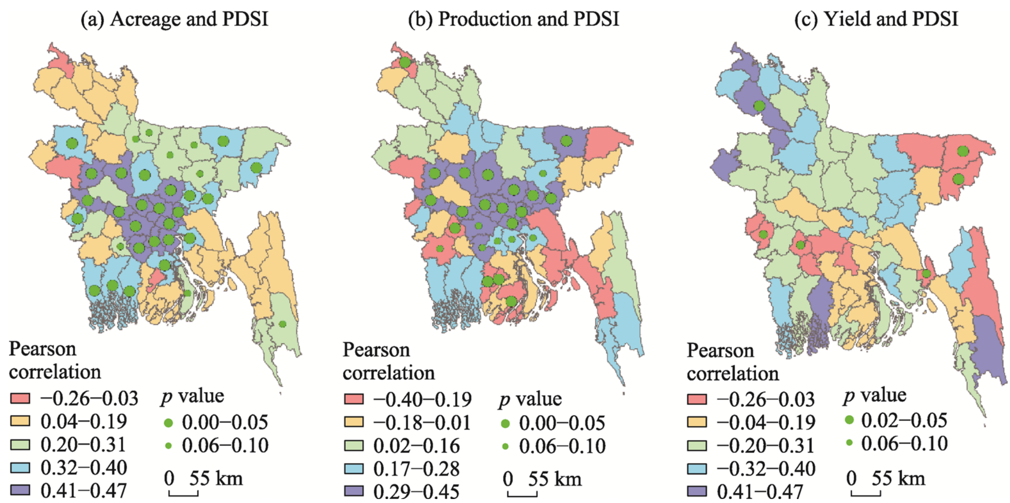

Figure 6 District-level Pearson correlation between area (a), production (b), yield (c) and PDSI

could be affected by wet spells, which could also be depicted using PDSI. In addition, the yield of *Aus* rice was found to have a significant positive correlation with PDSI in only one district and a significant negative correlation with PDSI in five districts, which suggests the effect of droughts on yield is not significant in most districts (Figure 6c).

Figure 7 presents the linear regression of standardized PDSI with standardized area, standardized production, and detrended and standardized yield, and the positively correlated, non-correlated, and negatively correlated districts were found. We found that PDSI has a significant influence on the area, which is revealed by a coefficient of regression (R^2=0.14) (Figure 7a). On the contrary, the districts where the *Aus* rice area is not correlated with PDSI have a very low coefficient (R^2=0.01) (Figure 7b). Moreover, production has high coefficient value for both positively (R^2=0.12) and negatively (R^2=0.12) correlated districts (Figures 6c and 7e). Finally, yield also has high coefficient value for positively correlated districts (Figure 7f), and negligible value for non-correlated and negatively correlated districts

(Figures 7g and 7h). PDSI explained about 14% variability of the cultivation area for the regions where PDSI had a significant positive correlation with drought (Figure 7a). Around 12% variability of the production might be explained by drought for the positively correlated districts (Figure 7b).

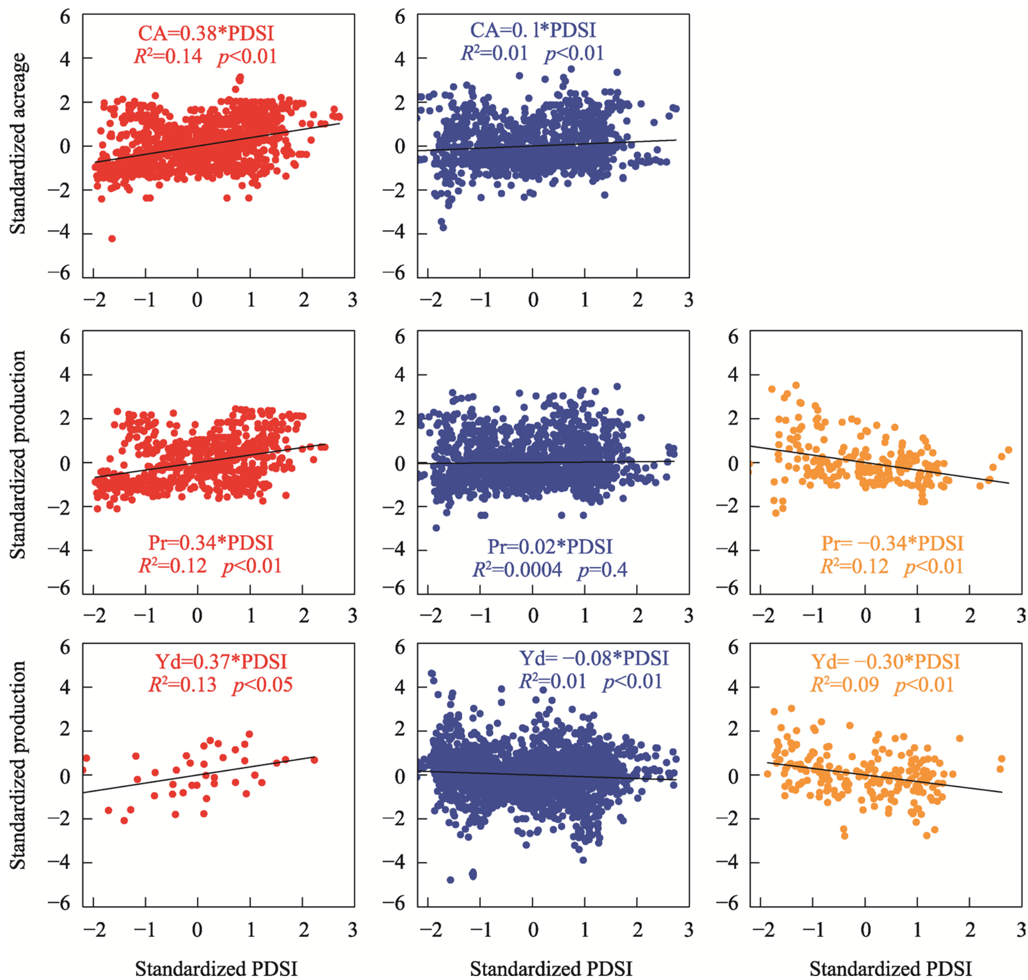

Figure 7 Linear regression between standardized PDSI and standardized acreage (a, b), standardized production (c, d, and e), and detrended and standardized yield (f, g, and h). The districts with positive correlation, no correlation, and negative correlation are presented in column 1, column 2, and column 3, respectively. CA, Pr, and Yd represent the standardized area, standardized production, and detrended and standardized yield, respectively.

4 Discussion

4.1 Attribution analysis of acreage, production, and yield of Aus rice

This study detected an unexplored pattern of agricultural drought in the pre-monsoon season, and its relationship with the trends of area, yield, and production of *Aus* rice in Bangladesh from 1980 to 2018. The knowledge gap fulfilled by this study is that the agricultural drought is an important contributing factor to the decrease of the area and production of *Aus* rice in Bangladesh.

The significant positive correlation between PDSI and the area of *Aus* rice in 33 districts (Figures 6a and 7a) and the significant positive correlation between PDSI and production of *Aus* rice in 19 districts (Figures 6b and 7b) are compelling evidence of drought impact on *Aus* rice. Low soil moisture, extreme heat (>40°C in March-May), and false onset of monsoon with breaks in precipitation result in poor crop establishment (Selvaraju and Baas, 2007). Reduced nutrient uptake and lessened microbial activity in the soil occur due to the small amount of soil moisture during drought, which affects crops. Increased temperature associated with drought retards the photosynthesis capability of C3 plants (Yang *et al.*, 2006) as the optimum temperature of paddy rice growth is between 25°C to 35°C (De los Reyes *et al.*, 2003). The reduction of the area occurs as the lessened soil moisture makes sowing of seeds impossible during the drought period, or the seedlings become desiccated and die. The similar impacts of droughts have also been reported by Rahman *et al.* that drought started from early December and prevailed until May in the *Haor* areas of northeastern Bangladesh (Rahman *et al.*, 2018), where droughts and flash-floods are the most devastating climatic extremes (Rahman *et al.*, 2018).

Droughts significantly reduced the yield of *Aus* rice in only one district (Figure 6c). The fact might be explained by the high-yielding rice varieties, increasing fertilizer and pesticide utilization, expansion of irrigation facilities, and agricultural mechanization. Some rain-fed rice may have transformed into an irrigated or at least partially irrigated rice. Yield in central and southern Bangladesh is still below 2.5 tons ha^{-1} where drought has increased at the highest rate.

4.2 Potential effects of irrigation dynamics

Districts with a higher percentage of groundwater-based irrigation facilities showed a lower correlation with area, production, and PDSI of *Aus* rice in the *Aus* season. It proves that irrigation can significantly contribute to solving the drought problem in this season. Our findings have been compared with the maps of irrigation-based cropland types (Figure 8a), area equipped for irrigation (Figure 8c), trend of increasing irrigation area (Figure 8d), area irrigated with groundwater (Figure 8e), as well as area irrigated with surface water (Figure 8f) to gain a better insight about drought influence on acreage, production, and yield of *Aus* rice.

Drought was found to have negative impacts on *Aus* rice in the regions with more rain-fed area. For the correlation of PDSI and cultivation area, mostly the districts with p-value < 0.05 (high drought influence) (Figure 7a) contain 20% to 80% combined rain-fed and irrigation minor irrigation regions (Figure 8a). This situation is also true for the correlation of PDSI and production (Figures 7b and 8a), except Faridpur, Gopalganj, Madaripur, Shariatpur, and Chandpur where local management practices may make p-value between 0.05 to 0.1 (relatively less drought impact on production).

Irrigation facilities cover less than 80% of total cropland area and 67% of the total area in the drought-affected districts (Figures 8b and 8c, and Table S2), and the trend of enhancing irrigation facilities is relatively lower (Figure 8d). In some regions of Bangladesh, groundwater-dependent irrigation coverage is between 10% to 60%, and surface-water based irrigation is between 35% to 100% (as a percentage of total equipped area). In the sowing time of *Aus*, rainfall is relatively less (180–280 mm) (Figure S2), and drought years are relatively characterized by comparatively reduced rainfall (Figure S4). Rainfall anomaly map of

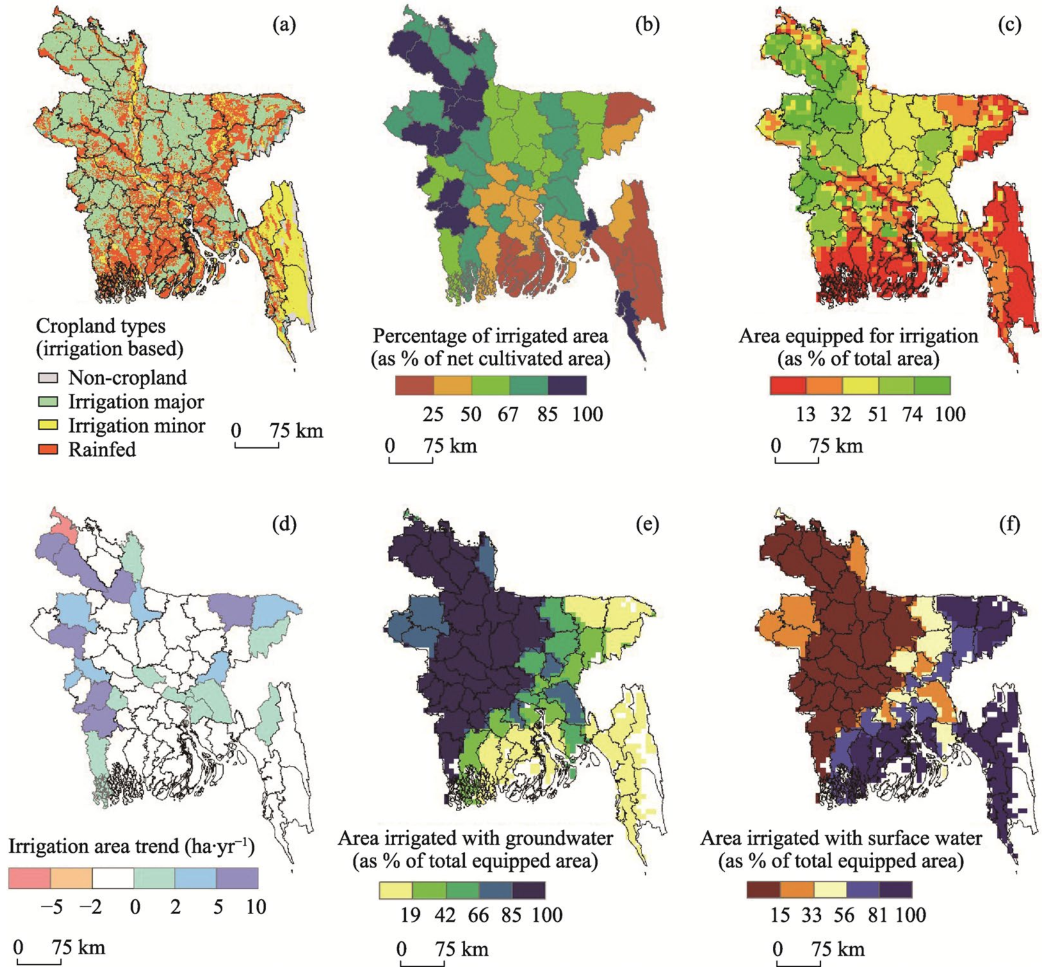

Figure 8 Map of irrigated and rain-fed cropland in Bangladesh (a), irrigated lands in 2016 (referring to the district-level percentage of total acreage) (b), area equipped for irrigation (referring to the percentage of total area with significant trends) (c), trend of irrigation coverage increase (2011–2016) (only significant trends are presented) (d), area equipped with groundwater (e), and area equipped with surface water (f) (referring to the percentage of total equipped area)

1980–2018 reveals that rainfall reduces by –400 to –700 mm/season (Figure S5) in the drought-affected pre-monsoon season. Despite of high coverage of irrigation facilities (Figure 8b), an increasing trend of droughts was observed in Dhaka, Natore, and Naogaon (Figures 1 and 5d, and Table S2). It might be due to that industrial development impacted water scarcity in Dhaka, and localized groundwater withdrawal-induced droughts in Natore and Naogaon. Therefore, lack of surface water and groundwater for irrigation during drought years could have caused the *Aus* rice to be vulnerable to droughts.

International rivers are the major irrigation source in Bangladesh (Rahman and Rahaman, 2018). Although irrigation area has increased in Bangladesh in recent years, the northeastern, southeastern, several central, and southern districts are mainly dependent on surface water-based irrigation where the impact of droughts on *Aus* is high. That might be explained by the fact that river discharge has drastically been reduced, especially in the dry season (January to May) due to the water diversion projects of India in the upstream. For example, after the inauguration of the Farakka-barrage by India in 1975, a severe reduction of maximum water discharge was reported between March to May. In addition, the maximum, average, and minimum water discharge of the Ganges has been reduced to 23%, 43%, and 65% from January to May, respectively, after the Ganges Water Sharing Treaty in 1996 (Rahman and Rahaman, 2018). As April and May are the transplanting and growth period for *Aus* rice, the area and production of this rice are affected by drought due to water scarcity. An increase of salinity in surface water due to the water diversion irrigation projects by India also hinders the surface water-based irrigation in coastal areas of Bangladesh (Murshed and Kaluarachchi, 2018). Alternatively, as yield is calculated on the remaining rice area that has already withstood droughts due to the irrigation or local management practices, it is the least affected by drought.

4.3 Potential drought mitigation measures for Aus rice

Under the auspices of the Government of the People's Republic of Bangladesh, limited irrigation has been applied to *Aus* rice fields since 2013 to support 8300 farmers by the DAE and the Ministry of Agriculture (MoA). The development and distribution of drought-tolerant seeds by BRRI and Bangladesh Institute of Nuclear Agriculture (BINA) might also improve the drought resilience of paddy rice. Moreover, planting the *Braust* (combining *Boro* and *Aus* variety) might be another viable option to cope with the drought for enhancing paddy rice production in Bangladesh, which has been developed by advancing the cultivation season (Islam *et al.*, 2017).

5 Conclusions

Agriculture, mainly rice, exists in over 70% of the territory of Bangladesh, and *Aus* rice is the most vulnerable to droughts due to anthropogenic and natural causes. In this study, we collected all the official statistical data of *Aus* rice and PDSI data at the district level from 1980 to 2018, and analyzed the spatial and temporal pattern of the changes in area, yield, and production of *Aus* rice as well as droughts. We found a significant decrease in area and production of *Aus* rice while the pre-monsoon droughts significantly increased in 88% area of Bangladesh from 1980 to 2018. Droughts contributed to reducing area and production of *Aus* rice in 52% and 23% of districts, respectively. We also identified the drought-affected *Aus* rice areas and the districts with significantly increasing irrigated area escaped the impacts of drought. The outcomes of this study are helpful to understand the impacts of drought on the *Aus* rice that might contribute to decision-making for national food security in Bangladesh.

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