On the Utility of Agronomic Monsoon Onset Definitions for Rainfed Aman Rice in Bangladesh

Working Paper No. 286

CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS)

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Photos:

Abstract

The monsoon-season '*aman*' rice crop contributes approximately 40% of total rice production in Bangladesh, where per-capita rice consumption rates are among the highest in the world. *Aman* rice is primarily rainfed and relies largely on monsoon rainfall, more specifically monsoon onset and withdrawal. *Aman* rice farmers' perception on the monsoon onset for the preparation of seedling does not necessarily coincide with typical meteorological onset definitions and varies with different locations. Therefore, agronomic definitions of monsoon onset, rather than meteorological definitions are needed in order to produce climate forecast information that can better support smallholder farmers' decision making, and the definitions should be tailored for different regions. In this study, we analyzed historical daily rainfall from three regional weather stations across a north-south gradient in Bangladesh where rainfed transplanted rice is the dominant summer crop. We defined threshold numbers including the duration of the initial wet spell, amount of rainfall received during the initial wet spell, length of dry spell during the monsoon, and the maximum amount of rainfall received during the dry spell to develop a set of actionable and region-specific agronomic onset definitions. Because transplanting dates can affect crop productivity, a region-specific onset definition was evaluated in terms of crop model simulated attainable yields in comparison with the results of (a) conventional meteorological onset defined by the quantity of rainfall received and (b) static onset date definitions. When year-to-year varying agronomic onset definition was used predicted attainable yields were higher than those derived from traditional fixed onset date in the case of fully rainfed condition. If irrigation is available at the time of transplanting, however, simulated yields did not show distinctive differences between the different onset methods, underscoring how irrigation can be used as a climate-smart adaptive strategy to cope with monsoon variability. Our tailored agronomic definitions of monsoon onset can be used to assist rainfed rice farmers in choosing more favourable dates for the establishment of seedbeds and transplanting, especially when more advanced seasonal or sub-seasonal forecasts are available in addition to real-time and high-resolution rainfall monitoring.

Keywords

DSSAT, crop modeling, rainy season, South Asian monsoon, climate services, Bangladesh *aman* rice

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Contents

Acronyms

ADS	Amount of rainfall received during the post-onset dry spell
AWS	Amount of rainfall received during the initial wet spell
BMD	Bangladesh Meteorological Department (BMD
CERES	Crop Environment Resource Synthesis
DSSAT	Decision Support System for Agrotechnology Transfer
LDS	Length of post onset dry spell
LWS	Length of the initial wet spell

1. Introduction

In Bangladesh, rice (*Oryza sativa*) is the primary staple food providing calories to a population of more than 165 million people (World Bank, 2019). The tropical climate of Bangladesh allows three rice growing seasons: aus, aman and boro. The aman rice is grown during the summer monsoon season, and tends to be transplanted in July or August and harvested from November through December. Harvests of aman rice contribute approximately 40% of total rice production in Bangladesh, although yield can be variable given that the crop is vulnerable to climate-related risks including drought and flash floods (Hussain, 2017; Mahmood et al., 2003). Early onset of the monsoon and thus excessive rainfall can damage aman rice at the seedling stage, causing delays in transplanting that can affect the productivity of both the rice and subsequent crops grown in rotation (Mahmood et al., 2004; Shelley et al., 2016). Where precipitation is insufficient, drought can have harmful effects on the growth of aman rice causing retardation in growth at the seedling stage and yield reduction due to water stress that affects pollen formation and embryo development during the flowering and reproductive stage (Mahmood et al., 2004; Shelley et al., 2016; Wassmann et al., 2009). On the other hand, a significant delay in transplanting due to a late arrival of the monsoon rains can potentially result in spikelet sterility and subsequent yield loss caused by water stress during the panicle emergence and the grain filling stage respectively (Kabir et al., 2014; Nahar et al., 2009).

In developing countries like Bangladesh, smallholder farmers often have limited means to cope with climate-related risks. Modification of planting dates are however an option that has been shown to mitigate these risks (Balwinder-Singh et al., 2019), and shifting the planting window to minimize risks during critical growth stages can be one of the best approaches that farmers are relatively able to act upon (Sultan et al., 2005). In Eastern Indo Gangetic Plains that include Bangladesh, West Bengal in India, and parts of Nepal, rainfed rice farmers start to prepare for nursery seedbed once the monsoon arrives and then transplant the seedling when there is sufficient water available for repetitive wet tillage (Gopal and Kumar, 2010). Normally rainfed *aman* rice farmers in Bangladesh prepare their nurseries on June 15 and wait for the first rainfall to prepare their field before transplanting with 25-30 days old seedlings (BRRI, 2019). Considering the heavy reliance on the monsoon by rainfed *aman* rice farmers for nursery establishment and transplanting, reliable forecasts of monsoon onset are a crucial component for effective climate information services in Bangladesh.

Skillful climate forecasts should be preceded by well-defined monsoon onset (Stiller-Reeve et al. 2015). There are many varying definitions of monsoon onset dates in the literature. Some examples include definitions based on the regional change in seasonal pattern of rainfall or convective activity (Tao, 1987; Ananthakrishnan and Soman, 1988; Lau and Yang, 1997), the change in direction of prevailing winds (Holland, 1986), or combined wind-convection criteria (An et al., 1998; Matsumoto, 1997; Wang and Wu, 1997). In Bangladesh, different monsoon definitions present different monsoon onsets dates. Stiller-Reeve et al. (2015) collated monsoon progressions over Bangladesh based on 11 different monsoon definitions found in literature. The comparison showed a similar patterns of monsoon progress, though with some exceptionally early onsets. They also demonstrated that the science-based monsoon onsets do not necessarily agree with farmers' perceptions, which also tend to differ by location. As a consequence, they concluded by emphasizing the importance of the end-user engagement and participatory approaches to the development of agricultural climate information services. Similarly, the development of advanced forecasting systems and climate information services is unlikely to be successful without the engagement of end users - namely rice farmers – including a thorough understanding their perceptions and needs (Brooks, 2013; Carr et al., 2019; Orlove et al., 2010; Vaughan et al., 2019).

Keeping agricultural applications in mind, local-scale agronomic definition of monsoon onsets have been developed and applied over Africa and South Asia (Marteau et al., 2009; Moron and Robertson, 2014; Fitzpatrick et al., 2016). This approach is based on determining threshold parameters describing the initial wet spell and post-onset dry spell (i.e., duration and amount of rainfall amount received during those periods) based on long-term daily rainfall analysis. The threshold numbers were defined to ensure proper soil conditions for crop establishment and growth, and to avoid false onsets that can result in early crop failure. These agronomically relevant definitions tend to differ from those used by meteorologists and the climate science community. However, detailed analysis using agronomic onset definitions have been carried out only in a few countries in Africa (cf. Dodd and Jolliffe, 2001; Marteau et al., 2009; Marteau et al., 2011) and in India (Moron and Robertson, 2014). Recently, in a large-scale analysis at the scale of the Indian subcontinent domain, Fitzpatrick et al. (2016) analyzed the spatial coherence of the agronomic monsoon onset using satellite-derived precipitation data, but no focus on Bangladesh was placed. To our knowledge, no efforts have however been made to determine agronomically relevant onset criteria in Bangladesh. In addition, none of the previous studies have evaluated the utility of localized agronomic definitions against those more commonly employed by meteorologists that are based mainly on cumulative rainfall or other meteorological variables

(e.g., wind direction, water vapor flux etc.). Furthermore, the benefits of the agronomic definitions to agricultural decision makers have never been quantified in terms of crop yield.

In this study, we analyzed historical daily rainfall data from three regional weather stations across a north-south gradient in Bangladesh in locations where rainfed *aman* rice production predominates. Utilizing these data, we defined threshold numbers for agronomic onset definitions. We also evaluated the monsoon onset definitions based on the attainable yields of *aman* rice using the Decision Support System for Agrotechnology Transfer (DSSAT)- Crop Environment Resource Synthesis (CERES) - rice model. The tailored agronomic definitions of monsoon onset have potential to help rice farmers make improved decisions on the timing of nursery preparation and transplanting, especially when more advanced seasonal or sub-seasonal forecasts are available in addition to real-time high-resolution rainfall monitoring.

2. Materials and methods

2.1.Weather data

Daily precipitation, minimum and maximum air temperature, sunshine hours, global solar radiation, relative humidity and wind speed for the period 1981-2017 were provided by the Bangladesh Meteorological Department (BMD). Three locations were considered according to the availability of data necessary for both the implementation of the monsoon onset method and crop modeling: Barishal (22.70ºN, 90.37ºE), Jashore (23.18ºN, 89.16ºE) and Rajshahi (24.36ºN, 88.65ºE) in Figure 1. Rainfed *aman* rice farming is dominant in these districts and therefore the onset of the rainy season is highly relevant as it influences the environmental suitability of determining suitable conditions for crops establishment. The climatological 1981-2017 annual cycle of air temperature, precipitation and solar radiation is provided in Figure 2.

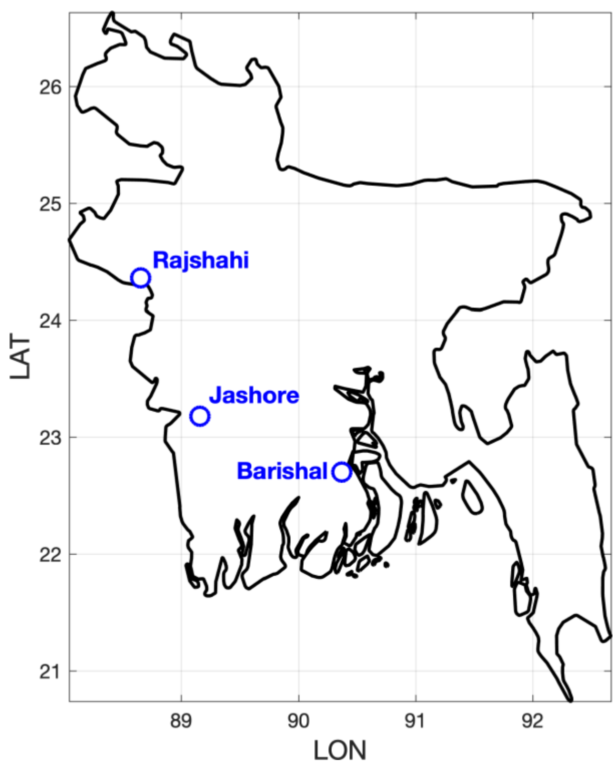

Fig. 1. Map of Bangladesh showing the location of the three weather stations used.

An important input variable for crop modeling is solar radiation. Unfortunately, this variable is rarely measured by synoptic weather stations, including many stations maintained by BMD. Instead, sunshine hours are more readily available. The empirical regression-based Angström-

Black linear model (Ampratwum and Dorvlo, 1999) was used to estimate solar radiation from sunshine hours. This model estimates solar radiation from the linear relationship between the ratio of measured and theoretical sunshine hours (calculated as a function of hour angle), and the clearness index, defined as the ratio between daily surface and extraterrestrial radiation on a horizontal surface. Solar radiation is calculated as the product between the clearness index and extraterrestrial radiation, which is obtained as a function of astronomical parameters for each latitude and day of the year.

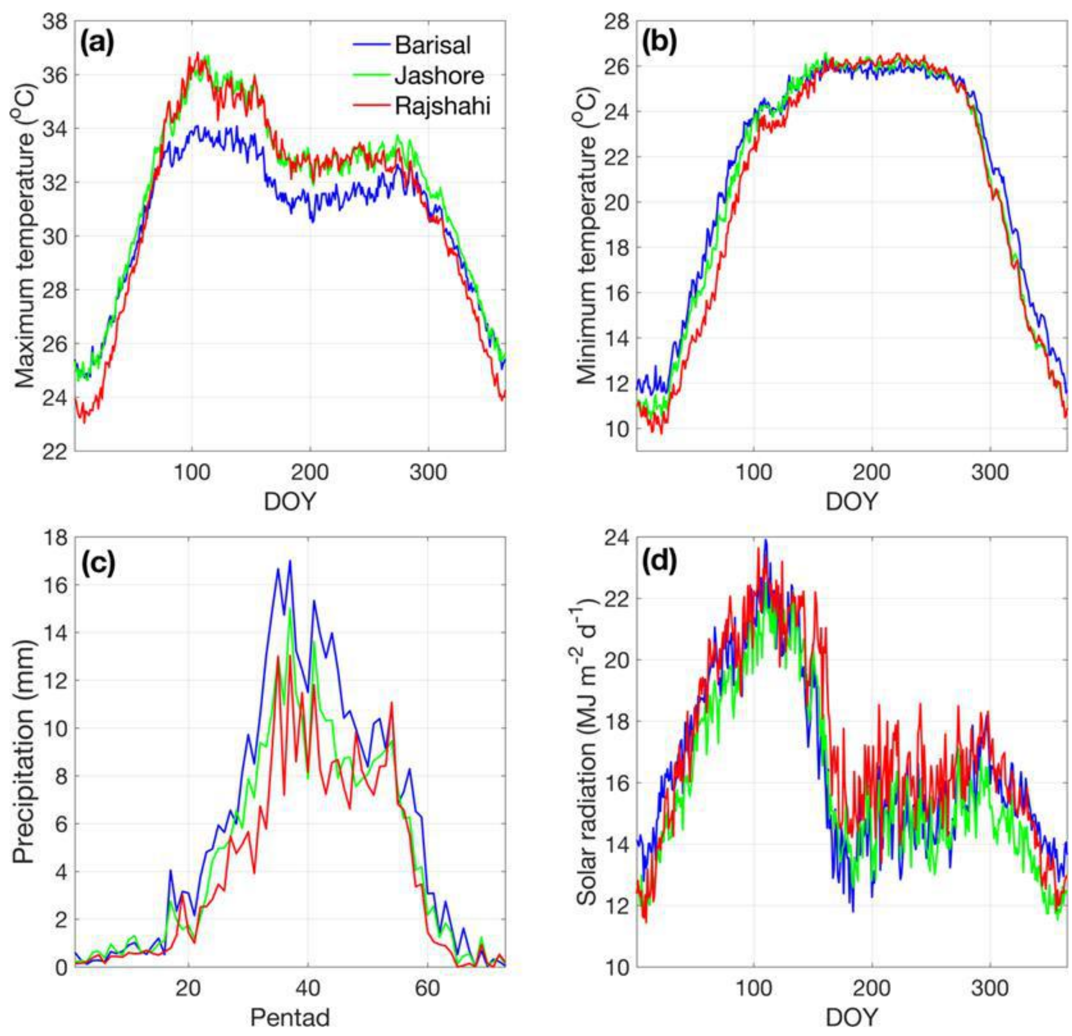

Fig. 2. Mean annual cycle (1981-2017) of (a) daily maximum temperature, (b) daily minimum temperature, (c) pentad precipitation, and (d) daily solar incoming radiation for the three locations in Bangladesh. DOY indicates 'day of year'

2.2. Methods

2.2.1. Defining a tailored agronomic monsoon onset

Several local and regional definitions of monsoon onset have been developed for different monsoon regions (e.g. Matsumoto, 1997; Stiller-Reeve et al., 2014; Zhang et al., 2002). In this work, we followed the agriculturally specific 'agronomic' monsoon onset approach proposed by Marteau et al. (2009) to define the local onset of the rainy season, initially developed for Africa. According to this method, the date of onset can be defined as the first wet day of one or two consecutive days receiving at least 20 mm of rain without any 7-day dry spell receiving less than 5 mm of rain during the following 20 days counted from the onset. However, Moron and Robertson (2014) state that the date of the agronomic onset should be calculated reflecting locally-varying precipitation parameters (e.g. length of wet/dry spells) to consider local climate conditions and water balance. As such, the following four parameters characterizing the daily rainfall evolution have to be defined at the local-scale: (1) the duration of the initial wet spell; (2) the amount of rainfall received during the initial wet spell; (3) the length of post onset dry spell to avoid false onsets related to pre-monsoon rainfall and (4) the maximum amount of rainfall received during the post-onset dry spell. Previous studies in Bangladesh have defined monsoon onset and withdrawal climatological dates from the first half of June and the first half of October (Ahmed and Karmakar, 1993) or early June (between May 31 and June 9) and early October (between October 3 and 12) (Hoque et al. 2011). Based on this information, we applied the period between May 15th and October 31st to compute the above presented parameters for the three selected weather stations in Bangladesh (Figure 1), The set of parameters was calculated using data from BMD weather stations to obtain a single set for each location and are presented in Table 1.

The *length of the initial wet spell* (LWS) considered as the minimum number of consecutive rainy days (rainfall ≥ 1 mm, number of days ≥ 1) was calculated by taking the average length of wet spells between May 15th and October 31st. BMD data indicate that wet spells for the three locations range from two to three days, with a standard deviation of one day over the three locations. Consequently, an LWS equal to the average length of wet spells plus 1 standard deviation can be considered as appropriate to define the initial wet spell (Table 1).

According to Moron and Robertson (2014), the *amount of rainfall received during the initial wet spell* (AWS) should be set following an agricultural water balance criterion considering the amount of water needed to fill dry soil. In order to have an estimate of the potential amount of water evaporated during the initial wet spell, reference evapotranspiration (ET_0) was calculated

using the FAO-56 method (Allen et al., 1998), during the end of the dry season period from March 1st and May 31th. An average ET_0 of 3 mm d^{-1} was obtained for the three locations. Consequently, an amount of rainfall ranging from 12 to 27 mm during the initial wet spell would be the minimum to wet the upper soil layers. Therefore, the average amount of rainfall accumulated during LWS for each station (AWS) ranging from 27 to 55 mm (Table 1) was applied as sufficient to wet the upper soil.

The average *length of post onset dry spell* (LDS), defined to avoid false onsets, during May 15th and October 31st (rainy season), was obtained by calculating the average length of dry spells in which the number of consecutive days with rainfall ≤ 1 mm could be summed. Our calculations show that dry spells length ranges from four to five days, with a standard deviation of one day. The latter suggests that a post-onset dry spell of 5-6 days (LDS, Table 1) is a reasonable parameter to avoid false monsoon onsets. Finally, the amount of rainfall received during the post-onset dry spell (ADS) was obtained by calculating the average ET_0 during the period May 15th and October 31st. Results show that ET_0 ranges from 3 to 4 mm d^{-1}, which would evaporate an amount of water of average 15 to 24 mm during the LDS (ADS, Table 1).

Thus, for each station, monsoon onset is defined as the first wet day (≥ 1 mm) from May 15th of the first wet spell of LWS days receiving at least the amount of rainfall AWS, without being followed by dry spell of LDS days receiving less rainfall than ADS in the subsequent 20 days from the onset (Table 1).

Table 1. Locations and parameters for monsoon onset calculation

Location	Latitude (º)	Longitude (º)	LWS (days)	AWS (mm)	LDS (days)	ADS (mm)
Barishal	22.70	90.37	4	55	5	15
Jashore	23.18	89.16	3	27	5	15
Rajshahi	24.36	88.65	3	31	6	24

LWS: length of the initial wet spell; AWS: amount of rainfall of the initial wet spell; AWS = amount of rainfall during the initial wet spell; LDS = length of the post onset dry spell; ADS = amount of rainfall of the post onset dry spell.

2.2.2. DSSAT CERES-Rice simulation

The DSSAT is a modular-based software package, which can simulate growth, developments and yields of more than 40 crops based on their interaction with soil and atmospheric environment at a spatially uniform field (Hoogenboom et al., 2019; Jones et al., 2003). The CERES – Rice model was initially developed by Ritchie et al. (1986) and embedded to the DSSAT package later (Jones

et al. 2003). The CERES-Rice model allows simulation of rice growth and developments under both lowland and upland conditions with various planting methods including dry sowing and transplanting. The input data to run the CERES-Rice model include daily weather data (i.e., daily maximum and minimum air temperature, solar radiation and precipitation), soil physical and chemical properties, genetic coefficients of a cultivar and management practices (i.e., planting date, irrigation, fertilizer application etc.). Rice crop phenology and the rate of crop development are simulated using the accumulated thermal time, called growing degree days, which is calculated from daily air temperature (Jones et al., 2003). The growing degree days required for transition to each growth stage are determined by user-defined genetic coefficients (Jones et al., 2003). Therefore, it is important to carefully calibrate the genetic coefficients of a target cultivar based on field experiments, before any application of the crop model. Detailed soil properties of each layer are needed to compute soil dynamics in the sub-modules for soil water balance, soil carbon and nitrogen balance, soil temperature and soil-plant-atmosphere. Total biomass of a crop is determined mainly by intercepted photosynthetically active radiation and reduced by several stress factors, such as extreme temperature or limited water or nitrogen availability (Ritchie et al., 1998).

The cultivar of *aman* rice we used in this study is BR 11, medium-duration *indica* variety. The BR11 *aman* rice is the most common and a high-yielding variety (Mahmood et al., 2003; Mahmood et al., 2004, Shelley et al., 2016). It remains one of the most widely grown genotypes in Bangladesh since its release in 1980 (Dey and Mustfali 2001). The genetic coefficients of BR 11 for the CERES-Rice model were taken from Hussain et al. (2014) and shown in Table A1. Each target location has different soil types including *Barisal, Gangni, Amnura* series and the detailed soil properties are shown in Table A2. We also adopted the rice management parameters used by Hussain et al. (2014). For instance, plant population at emergence, row spacing, and planting depth were 25 plants m^{-2}, 20 cm and 3 cm respectively. Inorganic fertilizers were applied N as urea, P as triple super phosphate and K as potassium chloride. Urea was applied at the final land preparation, 25 and 60 days after transplanting with same amount of 28 N kg ha^{-1}. Phosphate and potash fertilizers were applied 20 P kg ha^{-1} and 35 P kg ha^{-1} respectively at the time of land preparation. Note that transplanting age and transplanting date varied with different years when dynamic onset definitions were applied.

2.2.3. Evaluation of the DSSAT CERES-Rice model performance

In this study, we used well-calibrated parameters from Hussain et al. (2014) for genetic coefficients of the BR 11 *aman* rice variety. Information on major planting and management, and fertilizer application parameters were also taken from Hussain et al. (2014). This indicates we did

not consider specific fields with measured soil, weather inputs or yields but assumed hypothetical fields with general parameters and common practices shown in Hussain et al. (2014). Therefore, rather than taking a typical approach to crop model evaluation at a field scale (i.e., calculating difference between simulated and observed yields or phenological variables), we evaluated the model performance in terms of how well they capture inter-annual variabilities of long-term observed yields at an aggregate scale (i.e., division level observed yields). The model simulated rice yields with historical daily weather data from the three target stations, and these were compared with available division-level yield statistics retrieved from the Bangladesh Statistical Service during 1984-2013. The observed rice yields were linearly de-trended to remove non-climate signals from the yield time series. We then normalized the simulated and observed yields taking account of heterogeneities in management practices, soil characteristics and local weather within a division. Spearman's rank correlation was used to quantify how well simulated yields captured the inter-annual variabilities of the de-trended observed yields at a division level.

Simulated rainfed rice yields showed reasonable correlations ($\rho = 0.277$, $p = 0.139$ and $\rho = 0.297$, $p = 0.111$ respectively) with the observed yields in Barisal and Rajshahi divisions, but low correlation ($\rho = 0.162$, $p=0.394$) for Jashore (Khulna Division) as shown in Figure 3a. Particularly, Barisal and Jashore simulations could capture the extremely low yields due to drought in 1994 and 1997 (Selvaraju et al., 2006; Yu et al., 2010). Some opposite variations between the simulated and observed yields were also apparent, which could be attributed to processes that DSSAT could not simulate including disease or physical damage due to strong winds causing lodging and/or flooding.

Another way to confirm DSSAT rice performance was to that the DSSAT simulated yields could capture the optimal transplanting window when applied to 36 years of historical observed weather (1981-2016). Mahmood et al. (2003) tested different transplanting dates no later than August 15 (DOY 227) based on Bangladesh Rice Research Institute (BRRI) recommendations. Transplanting *aman* rice in August is typically recommended by the Bangladesh Agricultural Research Council to avoid yield loss due to flooding or drought when seedlings are still young (Chowdhury and Hassan, 2013). Planting after August 15 is risky in that rice is increasingly susceptible to dry conditions after the withdrawal of monsoon, particularly in Rajshahi division. Figure 4 shows the averages and standard deviations of the DSSAT simulated yields using historical Barisal weather data and different transplanting dates. The optimal transplanting window was found from the late July (DOY 211) to mid-August (DOY 226) where the mean/variance (uncertainty) of multiple simulated yields are higher/lower. This result also agrees with the findings of Kabir et al. (2014), who indicated that that transplanting in early August (August

4th) showed best simulated yields out of a range of transplanting dates from late July to early September.

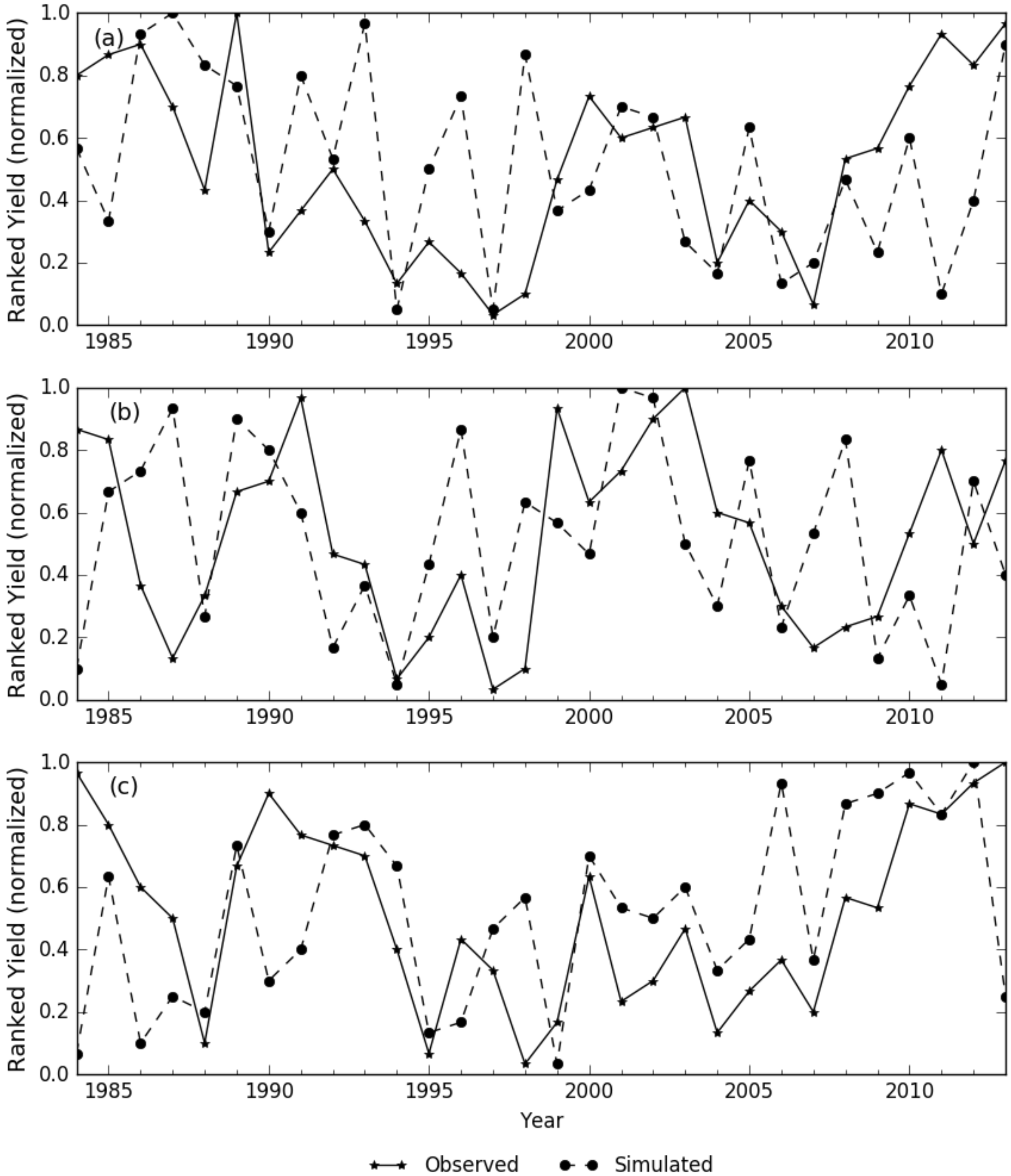

Fig. 3. Ranked observed yields in the division of Barisal (a), Khulna (Jashore) (b), and Rajshahi (c), and the simulated yields forced by the weather data from the corresponding BMD stations

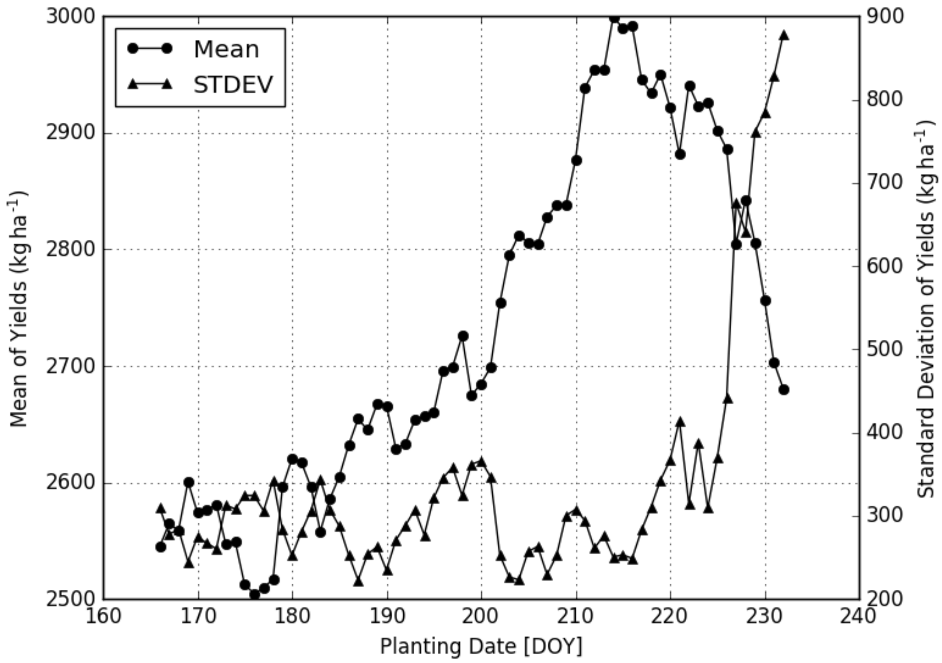

Fig. 4. Means and standard deviations of simulated yields using historical observed weather (1981-2016) in Barisal

2.2.4. DSSAT CERES-Rice simulations

Crop simulations under rainfed conditions

We investigated the effects of different onset definitions on nursery establishment, transplanting dates and rice yields under fully rainfed conditions in comparison with traditional practice. Here we assume that farmers establish their nursery when the monsoon starts and thus how farmers identify monsoon onset determines nursery establishment dates. First, many people in our target region, consider monsoon onset as a static date, the first day of the Bengali month of Ashar which is June 15th in the western calendar (Stiller-Reeve et al., 2015). In Bangladesh, farmers are normally encouraged by extension services to prepare their nurseries on June 15th and wait for the first rain for transplanting (Chowdhury and Hassan, 2013). Here we assume that farmers make their nursery on June 15th every year and transplant when the rule of Balwinder-Singh et al., (2019) is met. That is, farmers wait until the seedlings are at least 21 days old and their rice field has a ponding depth, at least 50 mm after heavy rainfall, enough for puddling.

Second, based on research evidence of farmers' own perceptions of the conditions associated with the monsoon onset demonstrated by Stiller-Reeve et al., (2015), we assumed that *aman* nurseries

were prepared on the normal onset dates. In the case of Barisal, the normal onset date is May 31st which was taken from the survey results in Chandpur, approximately 68 km from Barisal (refer to the Figure 4 in Stiller-Reeve et al., 2015). This is another case of using static onset dates and we applied the same rule of Balwinder-Singh et al., (2019) for transplanting. Third, farmers can take into account cumulative rainfall for nursery establishment considering year-to-year variations of the monsoon onset. Following Balwinder-Singh et al. (2019), we assumed that nursery is prepared when cumulative rainfall of three consecutive days within the nursery sowing window (from May 15 to August 15) is greater than 50 mm. The above same rule is applied for transplanting. Lastly, we applied the agronomic monsoon onset definition explained in Section 2.2.1 as the nursery establishment dates. Similar to the third onset definition, this approach also takes into account inter-annual variabilities of monsoon onsets but in a more sophisticated way by avoiding false onsets. Again, transplanting follows the same rule.

Crop simulations under irrigated conditions

In simulations that considered availability of irrigation to establish the *aman* crop, we relaxed water-constraints in transplanting compared to the fully rainfed condition, by assuming that farmers can apply irrigation to prepare fields for puddling and transplanting when the appropriate seedling age reaches. This experiment aims to reflect increasingly available shallow tube well and low-lift surface water irrigation systems in Bangladesh since the 1980s that have served to increase production and de-risk rice farming (Shelley et al., 2016). However, here we assume only limited irrigation use to facilitate timely crop establishment. In order words, irrigation was considered to be available only for puddling before transplanting, in order to overcome the sensitivity of rice plant to water stress that can increase shock during transplanting (Mahmood et al., 2003). After transplanting, our simulation proceeded considering rice growth supported only by naturally occurring rain. Here we define appropriate seedling age as 30 days old (Balwinder et al., 2015; Kabir et al., 2014; Sarker et al., 2013; Timsina et al., 1998; Yu et al., 2010). Therefore, in DSSAT simulations, transplanting dates are determined 30 days after nursery establishment which still depends on four onset definitions described above.

2.2.5. Statistical analysis

The effect of different onset definitions was quantified by comparing averages of simulated yields. Normality and the equal variance of the simulated yields from different onset definitions were first tested using the Shapiro-Wilk (Shapiro and Wilk, 1965) and Levene test (Levene, 1960) respectively. If the samples are normally distributed, we applied *t*-test for a hypothesis tests

of equal means from two different groups. Otherwise, a non-parametric test, Mann-Whitney-Wilcoxon test (Mann and Whitney, 1947) were used.

3. Results

3.1. Monsoon onset climatology

The averages and standard deviations of monsoon onset dates obtained from the agronomic onset definition for Bangladesh are displayed in Figure 5. Onset dates range from June 2nd to June 10th, with standard deviations of about two weeks. These mean values and range of variability agree with those reported by Ahmed and Karmakar (1993) and more recent works (Montes et al., submitted; Stiller-Reeve et al., 2014), as well as the spatial pattern of later onset dates over Rajshahi. The time series of onset dates indicate a relatively high interannual variability obtained by the agronomic method (Figure 5). Also, some correlation between onset dates was observed, with an average correlation coefficient of 0.3.

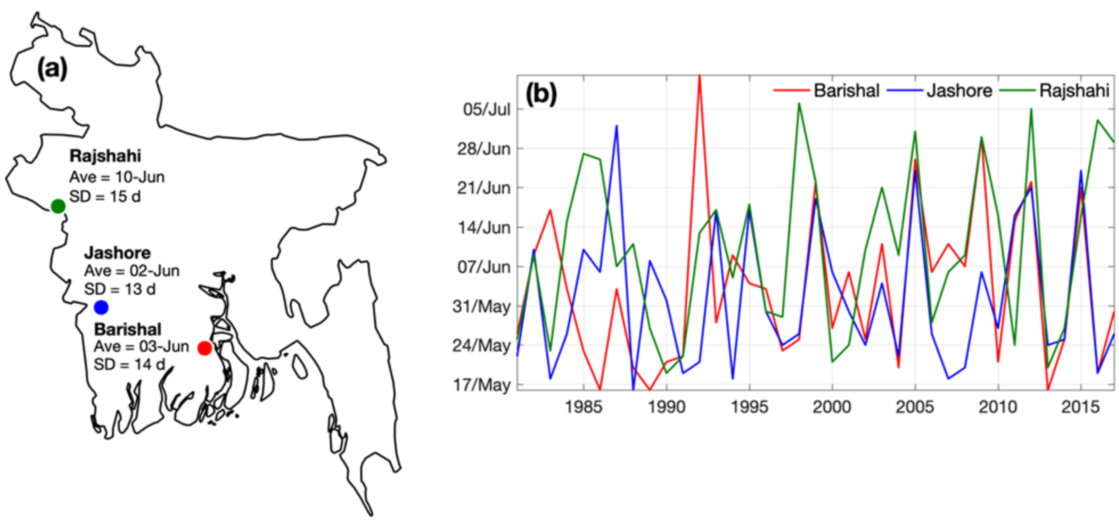

Fig. 5. (a) Map of Bangladesh showing the average monsoon onset date (Ave) and interannual standard deviation (SD in days) for the three locations. (b) Time series (1981-2017) of monsoon onset for the three weather stations shown in panel a.

3.2. Crop simulation under rainfed conditions

In this section, simulated rainfed rice yields using both dynamic onset dates and the static dates as criteria for nursery establishment are compared (see Section 2.2.4 for the definitions of two dynamic and two static onset dates). As a way to summarize our results, only simulations for Barisal station are included, which are presented in Figure 6. The rainfall-based onsets and

agronomic onsets are almost identical in Barisal with a few exceptions (Figure 6a). They are also within the range of the interannual variability of monsoon onset when calculated using locally relevant criteria (cf. Stiller-Reeve et al., 2015) in Chandpur (near Barisal), considering the earliest (May 11, DOY=131) and latest onset dates (June 30, DOY=181). For comparison, the conventional rainfall-based onsets started earlier than the agronomic onsets in several years because they did not take into account a dry spell after the initial wet spell. When using the agronomic definition, a delay in the monsoon onset beyond the reasonable transplanting window (no later than August 15, DOY=227) was observed in 1992. When the above-mentioned transplanting rule resulted in transplanting dates later than August 15th and seedling ages greater than 90 days, we assumed no transplanting and thus no crop yield available. Compared to the static onset assumption as a trigger for seed establishment (i.e., nurseries are prepared on June 15th, DOY=166, as generally recommended by national research and extension services), the dynamic onset definitions result in relatively early transplanting dates (Figure 6a).

The two dynamic onset definitions allowed higher yields than the two static definitions for many years (Figure 6c). For example, 15 out of total 25 years (60%) showed higher yields with the agronomic onset than the yields with nursery preparation on fixed June 15th. In addition, Table 2 shows that there is statistically significant difference in the means of the simulated yields between the static onset on June 15th and the other two dynamic onsets (i.e., p-value less than 0.05 proves that the hypothesis of equal means can be rejected). On average, the agronomic and rainfall-based onset dates allowed 417 and 71 kg ha^{-1} more yields than the static June 15th onset, respectively. This is mainly because relatively late nursery and transplanting dates derived from the conventional and static onset definition, particularly June 15th, resulted in simulations in which rice development was compromised due to adverse weather conditions and thus resulted in lower yields. For instance, late transplanting on August 3rd (DOY=215) in 1994 appears to have exposed the rice to significant water stress one month after the transplanting. Monthly rainfall in September and October in 1994 were 144 and 87 mm, respectively - much lower than the long-term averages (263 and 144 mm for September and October respectively). In 2004, relatively younger seedling due to late nursery establishment appears to have been more seriously damaged by exceptionally heavy rainfall in August and September (cumulative rainfall from the transplanting date, August 14th, DOY = 226 to the end of September reached 1400 mm in 2004).

Risk-averse farmers may not want to sow or transplant unconventionally early as a mechanism to avoid false onset and associated risks from uncertain whether. However, model simulation results suggest that static sowing date recommendations of June 15th appears to results in the loss of some of the benefits of early sowing or transplanting. Additionally, these results highlight the

potential value of developing operational seasonal or sub-seasonal forecasts that provide actionable information about the onset of the rainy season in agriculture.

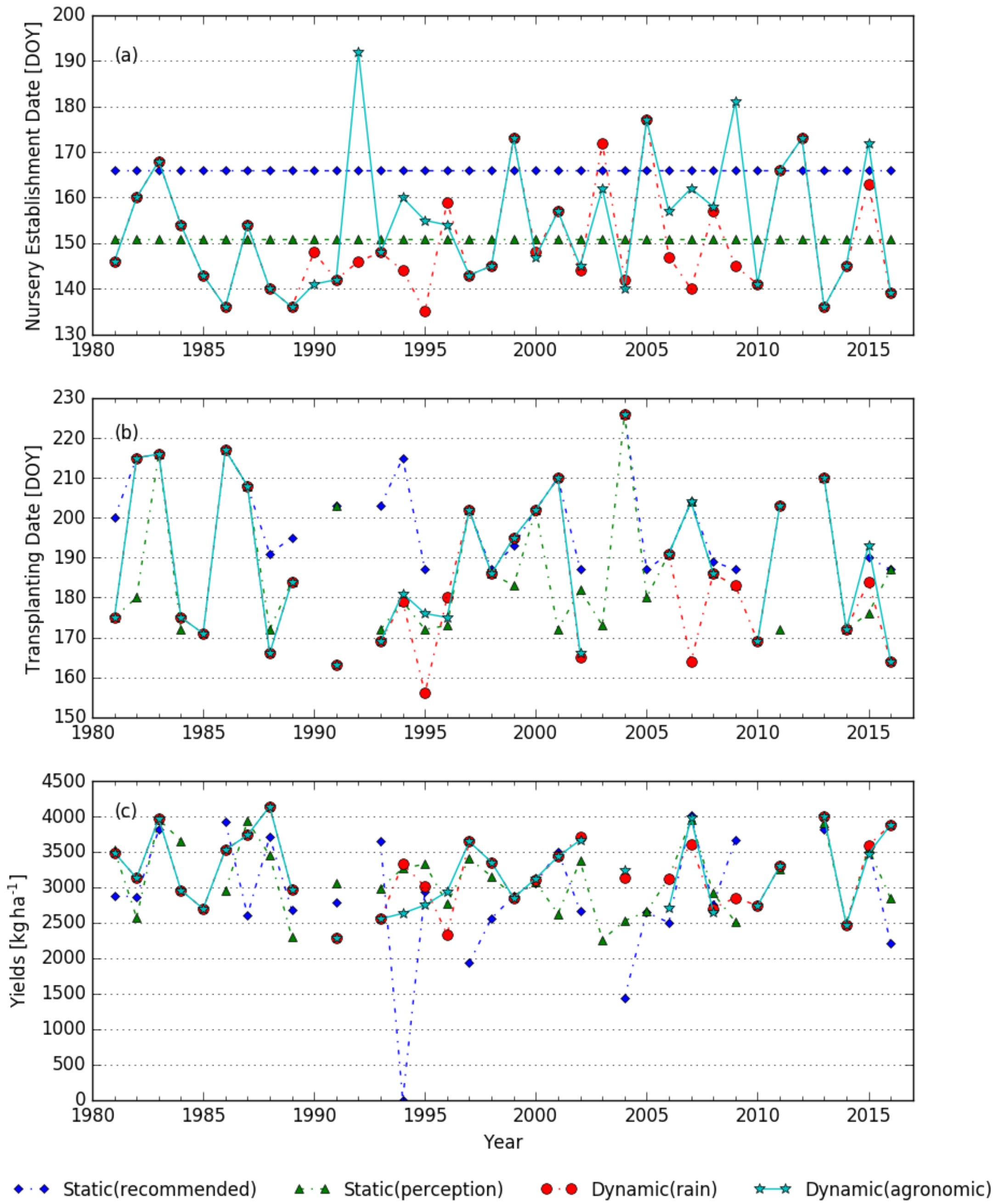

Fig. 6. Dates of nursery establishment (a), transplanting dates (b) and yields (c) based on different rules of nursery establishment under rainfed condition in Barisal. Static(recommended) and Static(perception) represents nursery established on June 15th and May 31st every year. Dynamic(rain) represents Nursery established when cumulative

rainfall of three consecutive days is greater than 50 mm while Dynamic(agronomic) is based on the agronomic definition described in Section 2.2.1

Table 2. p-values of *t*-test to test equal means of simulated yields using different nursery preparations dates

	Static(perception)	Dynamic(rain)	Dynamic(agronomic)
Static(recommended)	0.193	0.040*	0.047*
Static(perception)	-	0.455	0.595
Dynamic(rain)	-	-	0.905

Static(recommended): Nursery established on June 15th every year

Static(perception): Nursery established on May 31st every year

Dynamic(rain): Nursery established when cumulative rainfall of three consecutive days is greater than 50 mm

Dynamic(agronomic): Nursery established based on the agronomic definition described in Section 2.2.1

*p-value below 5% level of significance indicates rejection of the equal mean hypothesis

3.3. Crop simulation under irrigated conditions

When irrigation is available, farmers can more effectively avoid the risks of water stress at the reproductive stage which can be caused by delayed transplanting (Mahmood et al., 2003). As such, when these obstacles can be overcome through the use of irrigation to facilitate more timely transplanting, even static onset definitions could theoretically achieve a reasonable range of *aman* rice productivity compared to the inter-annually varying onset dates (Figure 7). Our simulations that include irrigation provide support to this hypothesis, as we observed no distinctive advantage of the agronomic onset definition compared to simple rainfall-based definition. This can be attributed to the similar threshold rainfall amount during the initial wet spell (55 mm during 4 days vs. 50 mm over 3 days) and because the DSSAT rice simulation does not take into account water stress during in nurseries period after monsoon onset. However, relatively late nursery establishment with the agronomic onset definition resulted in 207, 599 and 610 kg ha^{-1} lower yields than the rainfall-based onsets in 1992, 2009 and 2015 respectively.

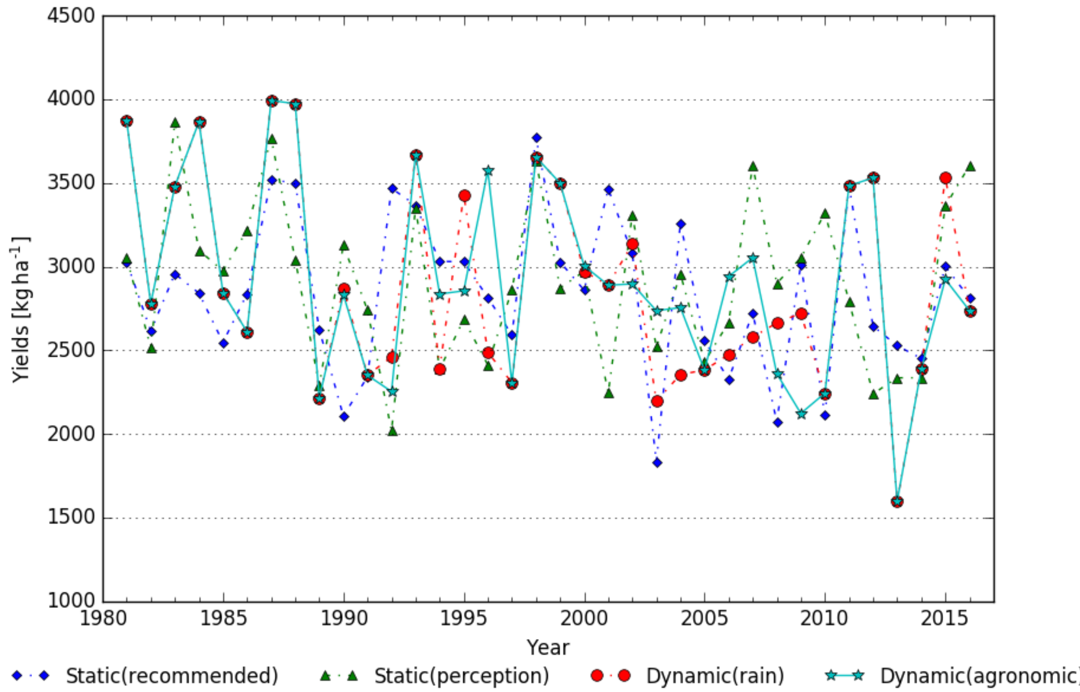

Fig.7. Simulated yields based on different rules of nursery establishment under partially irrigated condition in Barisal

4. Discussion

In this study, our main assumption is that farmers start to prepare nursery beds with the arrival of monsoon and wait until they have enough rain for puddling and appropriate seedling age is reached. The assumption was based on the farmer survey by Stiller-Reeve et al. (2015) which suggested that farmers in the central and western part of the country consider monsoon onset as approximately June 15th. This date, June 15th corresponds to the recommended date for nursery preparation by the extension services. Based on this assumption, our analysis proved that dynamic onset dates with relatively earlier nursery preparation than the traditional static date are more advantageous for producing higher yields. However, in reality, there are many cases that farmers are forced to miss the optimal or recommended dates for nursery preparation or transplanting. First, farmers who grow three crops a year (i.e., year-round farming) for subsistence do not have sufficient time to prepare nursery or transplanting of *aman* rice after harvesting crops from the previous season (Mahmood et al., 2004). They have to delay transplanting in spite of sufficient rain with the arrival of monsoon or being aware of higher risks of water stress during flowering or reproductive stages as a result of the delayed transplanting. Second, considering labor-intensive

farming in Bangladesh, scarce laborers during planting/harvesting hinder farmers' timely transplanting (Shelley et al., 2016). Third, in Bangladesh, a number of other factors constrain transplanting date – most importantly the relative elevation of fields and uncontrolled floodwater depths. This is one of the reasons that in Barisal, which has deep flooding, farmers tend to transplant very old seedlings and delay the transplanting dates. Particularly, Barisal is in an environment very unique to the other locations in this study. It is located in tidal floodplain and is highly affected by uncontrolled floodwater during the rainy season (Hamid et al., 2016). This provides unfavorable ecology for the high-yielding variety such as our target variety, BR 11 *aman* rice variety and thus farmers still prefer indigenous rice cultivars which is tall but has low yield potential to the modern varieties (Hamid et al., 2015).

Considering these realities, the present study has more room for further analysis. For example, the assumption that farmers start to make their nursery right after the monsoon onset might need to be relaxed considering the constrained resources in Bangladesh. In addition, Jashore and Rajshahi have less rainfall than Barisal and thus it is more difficult to meet the criteria for transplanting (i.e., minimum 50 mm ponding depth for puddling) with the current soil inputs. Therefore, some calibration of soil characteristics might be needed to continue to the similar analysis for those two locations.

5. Conclusion

In this study, we explored how different monsoon onset definitions affect rainfed *aman* rice yields in Bangladesh. In spite of a considerable literature on the onset of the monsoon in Bangladesh and South Asia, farmers tend to have different criteria for what determines and qualifies as on monsoon onset. As such, they tend to make agricultural decisions based on experience, perception or traditional definitions of what constitutes onset. In this paper, we applied two dynamic onset definitions (one conventional rainfall-based and a separate, tailored agronomic definition relevant to *aman* rice production in Bangladesh) to determine year-to-year varying dates for ideal nursery establishment in comparison with the static onset definitions. Then, we compared the resulting yields of the differently defined onset dates using DSSAT-CERES-Rice model. Dynamic onset definitions resulted in a wide range of nursery establishment dates when applied to 38 years of weather observations in Barisal. Under fully rainfed conditions, where transplanting fully depends on the quantity of rainfall received to achieve sufficient standing water for puddling, the model simulated yields with the dynamic onset definitions were generally higher than the ones with the static onset definitions. Our results indicate that these differences result from the increased possibility of losing the benefits of early transplanting that renders the crop less risk-prone to

drought and to late-season abiotic stresses when the static onset is used. Importantly, our simulations also indicate that where farmers have access to irrigation, they can overcome the risks of early season drought by applying irrigation. This exploratory study used some criteria in determining nursery establishment (50 mm of rainfall over three consecutive days) and transplanting (seedling age more than 21 days and ponding depth of at least 50 mm for puddling) from literature. These criteria may however need to be refined based on additional field survey data of farmers' most common crop management practices, especially in Jashore and Rajshahi which experience considerably less rainfall prior to and during the monsoon than Barisal. This preliminary work demonstrates the potential value of using a refined agronomic definition of the monsoon onset to assist farmers' decision making and improve the timeliness of *aman* rice nursery establishment.

Appendix

Table A1. Genetic coefficients of BR11cultivar title

P1	P2R	P5	P2O	G1	G2	G3	G4	PHINT
825.1	190.8	337.5	10.7	44	0.02	0.8	0.97	83

P1 (°C-d) is the thermal time required from seedling emergence to end of juvenile

P2O (hours): critical day length at which the plant development occurs at the maximum rate in photoperiod sensitivity phases

P2R (°C-d): extra thermal time required when daylength is one hour longer than P2O

PHINT (°C-d): fixed as 83 by the model meaning that the appearance of each subsequent leaf tip requires 83 (°C-d)

P5: Time period from beginning of grain filling to physiological maturity

G1: Potential spikelet number coefficient as estimated from the number of spikelets per g of main culm dry weight (less lead blades and sheaths plus spikes) at anthesis

G2: Single grain weight (g) under ideal growing conditions

G3: Tillering coefficient (scaler value) relative to IR64 cultivar under ideal conditions

G4: Temperature tolerance coefficient

Table A2. Soil properties of three target locations for DSSAT simulation

	SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI
BARISAL	5	0.273	0.425	0.533	1.00	0.12	1.24	1.74	47.5	51.4
	7	0.27	0.434	0.534	1.00	0.12	1.24	1.65	47	52.2
	12	0.281	0.443	0.536	1.00	0.12	1.22	1.59	48.4	51.1
	21	0.331	0.477	0.56	1.00	0.36	1.17	2.53	57.2	39.9
	30	0.261	0.427	0.534	0.6	0.09	1.42	1.56	45.6	53.6
	37	0.238	0.404	0.527	0	0.09	1.42	1.53	42.8	54.8
	51	0.186	0.366	0.523	0	0.15	1.46	1.57	33.7	66.2
	67	0.24	0.406	0.529	0	0.09	1.42	1.54	42.9	55

	SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI
JASHORE	12	0.29	0.43	0.53	1.00	20	1.38	1.46	51	40
	19	0.32	0.44	0.52	0.5	22	1.45	0.89	55	39
	36	0.31	0.44	0.54	0.35	22	1.41	0.45	53	40
	52	0.26	0.41	0.5	0	20	1.44	0.32	44	53
	70	0.134	0.377	0.467	0	20	1.38	0.22	32	66
	89	0.154	0.347	0.437	0	18	1.36	0.13	25	69
	110	0.068	0.243	0.337	0	16	1.2	0.1	10	66
	130	0.061	0.24	0.334	0	12	1.02	0.1	10	63

	SLB	SLLL	SDUL	SSAT	SRGF	SSKS	SBDM	SLOC	SLCL	SLSI
RAJSHAHI	15	0.117	0.268	0.419	1.00	0.68	1.23	0.54	20	63
	43	0.137	0.281	0.416	0.56	0.68	1.28	0.19	26	59
	66	0.211	0.338	0.4	0.336	0.09	1.35	0.17	43	43
	102	0.205	0.324	0.391	0.186	0.09	1.35	0.11	43	41
	140	0.24	0.383	0.422	0.089	0.09	1.28	0.9	45	42

SLB Depth, base of layer, cm

SLLL Lower limit, cm3 cm-3

SDUL Upper limit, drained, cm3 cm-3

SSAT Upper limit, saturated, cm3 cm-3

SRGF Root growth factor, soil only, 0.0 to 1.0

SSKS Sat. hydraulic conductivity, cm h-1

SBDM Bulk density, moist, g cm-3

SLOC Organic carbon, %

SLCL Clay (<0.002 mm), %

SLSI Silt (0.05 to 0.002 mm), %

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