

Reducing vulnerability of rainfed agriculture through seasonal climate predictions: A case study on the rainfed rice production in Southeast Asia



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ABSTRACT

Rainfed rice production needs to contribute more to the current and future world food security due to the increasing competition for limited water supplies including irrigation water. However, it is vulnerable to climate variabilities and extremes hence the utilization of climate predictions is crucial. In this study, the predictive accuracy and applicability of a seasonal climate predictions (SINTEX-F) were evaluated for rainfed rice areas where climate uncertainties are main constraints for a stable and high production. Outputs from SINTEX-F such as daily rainfall, maximum and minimum air temperatures, and wind speed were tested for Indonesia and Lao PDR through the cumulative distribution function-based downscaling method (CDFDM), which is a simple, flexible and inexpensive bias reduction method through removing bias from the empirical cumulative distribution functions of the GCM outputs. The CDFDM outputs were compared with historical weather data. Obtained results showed that discrepancies between SINTEX-F and the historical weather data were significantly reduced through CDFDM for both sites. ORYZA, an ecophysiological rice growth model that simulate agroecological rice growth processes, was used to evaluate the applicability of the SINTEX-F for grain yield predictions. Obtained results from on-farm field validation showed that the predicted grain yield was close to the actual grain yield that was obtained through optimum sowing timing given by the predictions. A normalized root mean square error between predicted and actual grain yield showed satisfactory model fit in predictions. This implies that SINTEX-F was applicable for improving rainfed rice production through CDFDM. However, CDFDM has a limitation in orographic precipitation, the high-resolution daily weather data or a sophisticated special interpolation method should be considered in order to improve the representation of the geographical pattern for the parameters derived from CDFDM.

1. Introduction

According to the Fifth Assessment Report from IPCC, the average combined land and ocean surface temperature increased globally by 0.85° C during the period 1880 to 2012. As a result, more extreme weather events such as droughts and floods occurred more frequently than before and crop yields have been negatively affected (IPCC, 2014). This change in climate causes serious problems in agriculture, especially in rainfed environments where crop production's water supply highly depends on rainfall.

Seasonal climate predictions are useful for decision making in agriculture (Meza et al., 2008) and many application studies have been carried out on various crops for predictions. Wheat yield predictions

were evaluated at the local and regional scale and adequate predictability was reported by Cantelaube and Terres (2005) and Marletto et al. (2007). Semenov and Doblas-Reyes (2007) also evaluated the seasonal climate predictions in wheat yield predictability and they reported a limitation of skill score for higher latitude areas like Europe and New Zealand. Ines and Hansen (2006) presented a method of application for seasonal climate predictions through bias-correction to be suitable to predict maize yield in semi-arid Kenya. Application of seasonal climate predictions in agricultural management increased average gross margins for maize farmers in Kenya (Hansen et al., 2009). Roudier et al. (2012) also quantified the economic value of seasonal climate predictions in millet production in Niger and they found that the seasonal climate predictions are effective at the time of bad years. The

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study of Malherbe et al. (2014) emphasized the use of the global coupled model to expect crop yield prediction outperformed. Despite these promising results in the application of seasonal climate predictions in crop yield predictions and agricultural decision making, no study has evaluated the applicability of seasonal climate predictions on rice production at the local scale in Asia, where the granary of world rice production and supply exist.

Rice is one of the major staples feeding around 3.5 billion people in the world. According to the projection, 560 million tons of rice is needed by 2035 to feed the world population which requires an increase of 120 million tons of rice production compared with the one in 2010 (GRiSP (Global Rice Science Partnership), 2013). Irrigated rice is the major ecosystem for world rice supply; however, the production should be diversified through other ecosystems like rainfed rice in order to deal with an increasing pressure brought about by the competition for limited water (Wassmann et al., 2009). Rainfed areas account for 33% of the total rice production area in the world but it provides only 19% of world rice production because its yield is low, only 2.3 t ha^{-1} on the average, which is lower than that for irrigated rice at 5.0 t ha^{-1} (GRiSP, 2013). Improving productivity in rainfed rice is imperative not only to enhance food supply for current and future demand but also to alleviate constraints for irrigated rice according to the world and regional climate change contexts.

Rainfed rice farming has high uncertainty in terms of the start and end of the rainy season, rainfall amount, and duration (Mackill et al., 1996). The probability of occurrence of abiotic stresses such as drought is also high during the growth period and their effect, particularly at critical growth stages, could cause substantial damage to the growth and nutrient use of the rice plant. Optimum time for sowing is essential to avoid adverse effects and for rice growth to occur under optimum flowering (Fukai, 1999) hence the application of seasonal climate predictions in crop models is one of the ways to make rainfed rice production more adaptive to climate change (Abedullah, 1998; Lansigan et al., 2000).

This study aimed to evaluate the applicability of seasonal climate predictions in rainfed rice areas of Southeast Asia, where the granary of world rice production and supply exist. In order to achieve this goal, we evaluated (1) the predictive accuracy of seasonal climate predictions at the local scale and (2) the applicability of seasonal climate predictions in a crop growth model for rice yield prediction.

2. Materials and methods

2.1. Study areas

In order to evaluate the predictive accuracy of seasonal climate predictions in wide areas of designated region, Indonesia and Lao PDR were selected as target countries to represent low and relatively high latitudes in the region.

Rice is the staple for Indonesia and Laos PDR, where per capita consumption is $127.4 \text{ kg year}^{-1}$ and $165.5 \text{ kg year}^{-1}$, respectively (GRiSP, 2013). Rainfed is one of the dominant ecosystems for rice production in both countries and this study targeted Central Java province in Indonesia and Savannakhet province in Lao PDR that account for 30% and 40% of the total rice area in each country, respectively (Amien and Las, 2000; Linquist and Sengxua, 2001). The most critical constraint in rice production in these provinces is drought stress (Schiller et al., 2006; Boling et al., 2016) that causes a water shortage during the crop growth period, resulting in yield loss. Average grain yield in rainfed rice is 3.5 t ha^{-1} on the average for direct-seeded rice and 1.2 t ha^{-1} on the average for transplanted rice in Central Java (Wihardjaka et al., 1999) and 2.4 t ha^{-1} on the average for wet-season rice in Savannakhet (Linquist and Sengxua, 2001).

2.2. Global coupled model and statistical downscaling

The Scale Interaction Experiment–Frontier Research Center for Global Change (SINTEX-F), which is a relatively high-resolution ocean–atmosphere coupled general circulation model to simulate the climatology and El Niño Southern Oscillation (ENSO) in the tropical Pacific (Luo et al., 2008) was used for this study. ENSO is highly correlated with South Asian monsoon through regulating the length of the rainy season (Goswami and Xavier, 2005); hence, predicting this climate mode is crucial for agriculture, especially for rice production in tropical Asia. The SINTEX-F is a GCM which has a predictability of ENSO at 9–12 months lead times with a resolution of $1.1^\circ \times 1.1^\circ$ (Luo et al., 2008) and provides daily weather parameters such as rainfall, maximum and minimum air temperature, wind speed. The outputs from SINTEX-F can't be directly applied for a crop model in specific areas because of its systematic error (bias), hence a dynamic or statistical downscaling is necessary for adaption study (Iizumi et al., 2011). The cumulative distribution function-based downscaling method (CDFDM), which is a bias reduction downscaling method to calibrate GCM daily data, was used to remove systematic errors through the empirical cumulative distribution functions (CDFs) of the SINTEX-F outputs and observed data (Iizumi et al., 2010, 2012). The CDFDM is an inexpensive method compared with the dynamical models and other sophisticated statistical models, and flexible to apply various daily variables, including daily mean, maximum, and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed (Iizumi et al., 2011).

The outputs from SINTEX-F were obtained from Japan Agency for Marine–Earth Science and Technology (JAMSTEC) for the designated grids (S6.2, E110.3 for Central Java, N16.5, E105.1 for Savannakhet) and the period from 1982 to 2014 with a 9-month lead time. The parameters were minimum and maximum air temperature ($^\circ\text{C}$), precipitation (mm d^{-1}), and wind speed (m/s). The data on wind speed from SINTEX-F was at 10 m above ground; thus, correction was made by using the following formula by Rosenberg et al. (1983):

$$u_1 = u_2 \ln\left(\frac{h_1/z}{h_2/z}\right) / \ln\left(\frac{h_2/z}{z}\right)$$

where u_1 is wind speed (m/s) at 2 m, u_2 is wind speed (m/s) at 10 m, h_1 , h_2 and z are 2, 10, and 0.05, respectively.

Data on locally observed long-term weather is one of the required datasets for CDFDM to obtain the empirical CDFs from daily SINTEX-F outputs and observed weather data within targeted grid. The data on locally observed long-term weather were acquired from the Indonesian Agricultural Environment Research Institute for Central Java and the Department of Meteorology and Hydrology of Lao PDR for Savannakhet. The periods of the datasets for Central Java were from 1987 to 2013, and the one for Savannakhet was from 1982 to 2013.

In order to evaluate the performance of CDFDM, mean error (ME) was computed using following formula;

$$\text{ME} = \frac{1}{n} \sum_{i=1}^n (P_i - O_i)$$

where, P_i is outputs of SINTEX-F or CDFDM, O_i is observed weather data (Walther and Moore, 2005).

2.3. Evaluation of applicability of SINTEX-F to rainfed rice areas

To evaluate the applicability of the seasonal climate predictions for grain yield prediction of rice varieties, ORYZA, an ecophysiological rice growth model that simulates the growth and development of rice under potential, water-limited, and nitrogen-limited conditions (Bouman and van Laar, 2006), was used for the simulation of designated varieties at

the study sites. The ORYZA requires daily weather data and crop data as inputs for dynamic simulation of agroecological rice growth (Bouman et al., 2001).

Indonesia where rice feeds > 200 million people was chosen as a case study for the applicability of seasonal climate predictions. Central Java was the target site of this study because rainfed rice area is dominant and largest among other provinces.

For ORYZA simulations, daily radiation ($\text{kJ m}^{-2} \text{d}^{-1}$) and daily vapor pressure (kPa) were also computed. Daily radiation was obtained through the following formula (Bristow and Campbell, 1984):

$$\text{SR/SRo} = a [1 - \exp(-bDTR^c)] \times 1000$$

where SR and SRo are the solar radiation on the ground and in the top levels of the atmosphere, respectively. DTR is the diurnal temperature range ($^{\circ}\text{C}$). a , b , and c are the empirical parameters.

Daily vapor pressure (kPa) was obtained through the following formula (Allen et al., 1998):

$$e_a = e^s(T_{dew}) = 0.611 \exp \left[\frac{17.27 T_{dew}}{T_{dew} + 237.3} \right]$$

where e_a is actual vapor pressure, T_{dew} is dew point temperature, $e^s(T_{dew})$ is saturation vapor pressure at the dew point temperature. According to Allen et al. (1998), minimum temperature (T_{min}) can be considered as T_{dew} hence the above formula can be also given as follows;

$$e_a = e^s(T_{min}) = 0.611 \exp \left[\frac{17.27 T_{min}}{T_{min} + 237.3} \right]$$

Crop data were prepared through on-station field experiments carried out at the research station of the Indonesian Agricultural Environment Research Institute. The long-term average annual rainfall in the area is 1459 mm. A large part of the rainfall occurs in the early rainy season, which is from October to February, and long-term average rainfall during the season is 966 mm. The late rainy season is from March to June and long-term average rainfall during the season is 445 mm.

Two types of on-station field experiments with rice varieties IR64 and Ciherang were conducted in the early and late rainy seasons during the period 2012 to 2014. These varieties are the most popular varieties among farmers in all ecosystems across the country. The first experiment was conducted to calibrate ORYZA for grain yield simulation (Exp-1) and the experimental treatments included two water managements (irrigated and rainfed) in the main plot, three nitrogen (N) dosages (0N, 60N, and 120N kg ha^{-1}) in the subplot, and two varieties (IR64 and Ciherang) in the sub-subplot, laid out in a split-split-plot design with four replications. Nitrogen fertilizer was applied in three splits: at basal, a first topdress at maximum tillering stage, and a second topdress at the panicle initiation stage. Phosphorus (P), potassium (K), sulfur (S), and zinc (Zn) were applied at 22, 90, 20, and 5 kg ha^{-1} , respectively, at basal as a general recommendation.

The second experiment was conducted to evaluate the effect of sowing date on crop growth and grain yield (Exp-2). The experimental treatments included two rice varieties (IR64 and Ciherang) in the main plot and sowing timing (first sowing timing as surrounding farmers started and 15, 30, and 45 days after the first sowing date) in the subplot, laid out in a split-plot design with four replications. Water management for the second experiment was rainfed and fertilizer was applied by following the general recommendation (120N, 22P, 90K, 5Zn kg ha^{-1}). Crop establishment for all experiments was done by dry direct seeding for the early rainy season and transplanting for the late rainy season. The minimum size of each experimental plot was 5 m \times 6 m. Pest management was done to control insects, diseases, and weeds.

Crop parameters were measured in terms of (1) date of occurrence of emergence, panicle initiation (PI), flowering (F), and physiological maturity (PM); (2) above-ground biomass at 14, 28, and 42 days after

emergence, PI, F, and grain filling (early wet season) and at 0, 14, and 28 days after transplanting (late rainy season), PI, F, and grain filling; and (3) yield components (panicle number density, spikelet number/panicle, % filled spikelets, 1000-grain weight) and grain yield (Dobermann and Fairhurst, 2000).

Exceedance probability (P) of cumulative rainfall was used to examine the characteristics of rainfall during the study. This was also applied for long-term rainfall data to identify extreme weathers in the study areas. The probability was obtained by the formula proposed by Boling et al. (2004). Annual or seasonal cumulative rainfall record was arranged in descending order and P was computed using following formula;

$$P = m/(n + 1)$$

where, m is a ranking number and n is total count.

2.4. Validation on grain yield simulation

On-farm field experiments were conducted in the early rainy season in 2013–2014 and late rainy season in 2014 in order to evaluate the performance of ORYZA simulation by seasonal climate predictions in grain yield prediction (Exp-3). The experiments were conducted in four villages (Sidomukti and Plemgede villages in Pati District, Megulung and Jadi villages in Rembang District) where much research on rainfed rice production had been conducted previously (Wihardjaka et al., 1999; Boling et al., 2008, 2016).

In the experiments, four different sowing dates were scheduled as follows: the first sowing date was determined by the seasonal climate prediction-based grain yield simulation, and the second, third, and fourth sowings were carried out 15, 30, and 45 days after the first sowing date. Crop establishment was by direct seeding and the size of the experimental plot was 5 m \times 6 m. Crop parameters were measured to determine phenology and grain yield. Surrounding farmers in each village were also surveyed to record their practices and measure grain yield under farmers' management.

2.5. Evaluation of model performance

Normalized root mean square error (RMSEn) was used to evaluate the performance of ORYZA in selected varieties. RMSEn measures the differences between the values predicted by a hypothetical model and the observed values (Loague and Green, 1991; Fayed et al., 2015). RMSEn is computed using the formula below:

$$\text{RMSEn} = \sqrt{\frac{1}{n} \sum_{i=1}^n (P_i - O_i)^2} \times \frac{100}{M}$$

where P_i is the predicted/simulated values, O_i is the observed/measured values, n is number of observations, and M is the observed mean value. Obtained RMSEn was evaluated by the following rating (Jamieson et al., 1991); excellent as $\text{RMSEn} < 10\%$, good as $10\% < \text{RMSEn} < 20\%$, fair as $20\% < \text{RMSEn} < 30\%$, poor as $30\% < \text{RMSEn}$.

Analysis of variance for the statistical comparisons was also carried out using Statistical Tool for Agricultural Research version 2.0.1 (IRRI, 2014).

3. Results

3.1. Examination of model performance for the bias reduction method

Figs. 1 and 2 show the results of a comparison of daily observed data (Obs) with SINTEX-F outputs (SINTEX-F) and CDFDM outputs (CDFDM) for minimum air temperature (T_{mn}), maximum air temperature (T_{mx}), wind speed (WS), and rainfall (RF). Fig. 1 contains the results for Central Java and Fig. 2 for Lao PDR. The obtained results showed that significant discrepancies identified on each parameter between Obs and

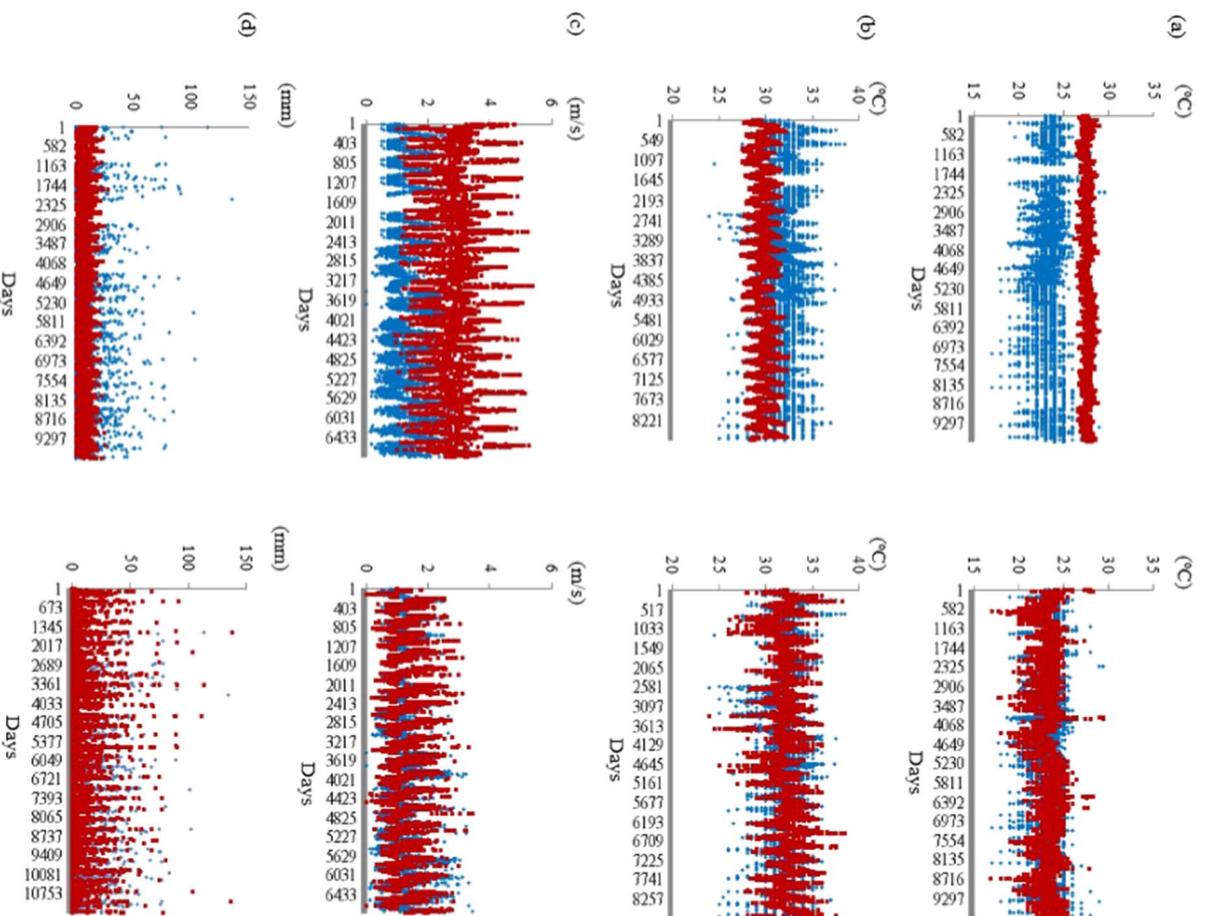


Fig. 1. Comparison of observed weather data (blue dots) to SINTEX-F outputs (red dots in the figures on the left side) and CDFDM outputs (red dots in the figures on the right side) for Central Java: (a) minimum temperature, (b) maximum temperature, (c) wind speed, and (d) rainfall. X axis shows the number of days for the run from January 1, 1987. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

SINTEX-F (left-hand graphs in Figs. 1 and 2) were minimized after the bias reduction procedure and all parameters became close to the observed weather data for both sites (right-hand graphs).

Table 1 shows the results of mean error (ME) for RE, T_{min} , T_{mx} and WS and it explains how close or far CDFDM and SINTEX-F are against Obs. The ME for both sites showed similar results that ME obtained through subtracting CDFDM from Obs was smaller than the one obtained through subtracting SINTEX-F from Obs. This means that CDFDM was closer to Obs than SINTEX-F hence bias in SINTEX-F was reduced through CDFDM in all four parameters.

To examine the reliability of the result from the bias reduction procedure, the performance of CDFDM was also evaluated on mean annual rainfall (AR) and number of days for sowing (DOS) in rice cropping for each site. Number of days for sowing was obtained through counting the number of days from the first rainfall to reach a required amount of cumulative rainfall for sowing. The annual rainfall of Obs was compared with that for SINTEX-F and CDFDM and the results are shown in Fig. 3. The results for Central Java and Savannahket look similar and AR for CDFDM was not significantly different from that for Obs. The AR of SINTEX-F was significantly higher for Central Java and significantly lower

for Savannahket which implies an overestimation in Central Java and underestimated in Savannahket through SINTEX-F. Table 2 shows AR for either the years of below normal ($P > 0.80$) or above normal ($P < 0.20$) and CDFDM for Central Java was similar to Obs when AR was below normal, SINTEX-F was similar to Obs when AR was above normal. For Savannahket, a clear trend was not found in both SINTEX-F and CDFDM.

Fig. 4 is the result of DOS for Central Java and Savannahket. For rice planting in rainfed areas, a certain amount of rainfall is required to assure crop establishment and local farmers wait for certain period after the onset of the rainy season prior to starting sowing. For Central Java, local farmers waited on average until cumulative rainfall was 139 mm and it took about 100 days before sowing took place accordingly for Obs. The CDFDM was 108 days, which was closer to the result of Obs without a significant difference. The result for SINTEX-F was 57 days and many fewer days than that of Obs. For Savannahket, local farmers waited for cumulative rainfall of 72 mm and this took 38 days, 33 days, and 19 days for Obs, CDFDM, and SINTEX-F, respectively. Although a significant difference was given to CDFDM and SINTEX-F compared with the result for Obs, the result for CDFDM was close to the one for Obs.

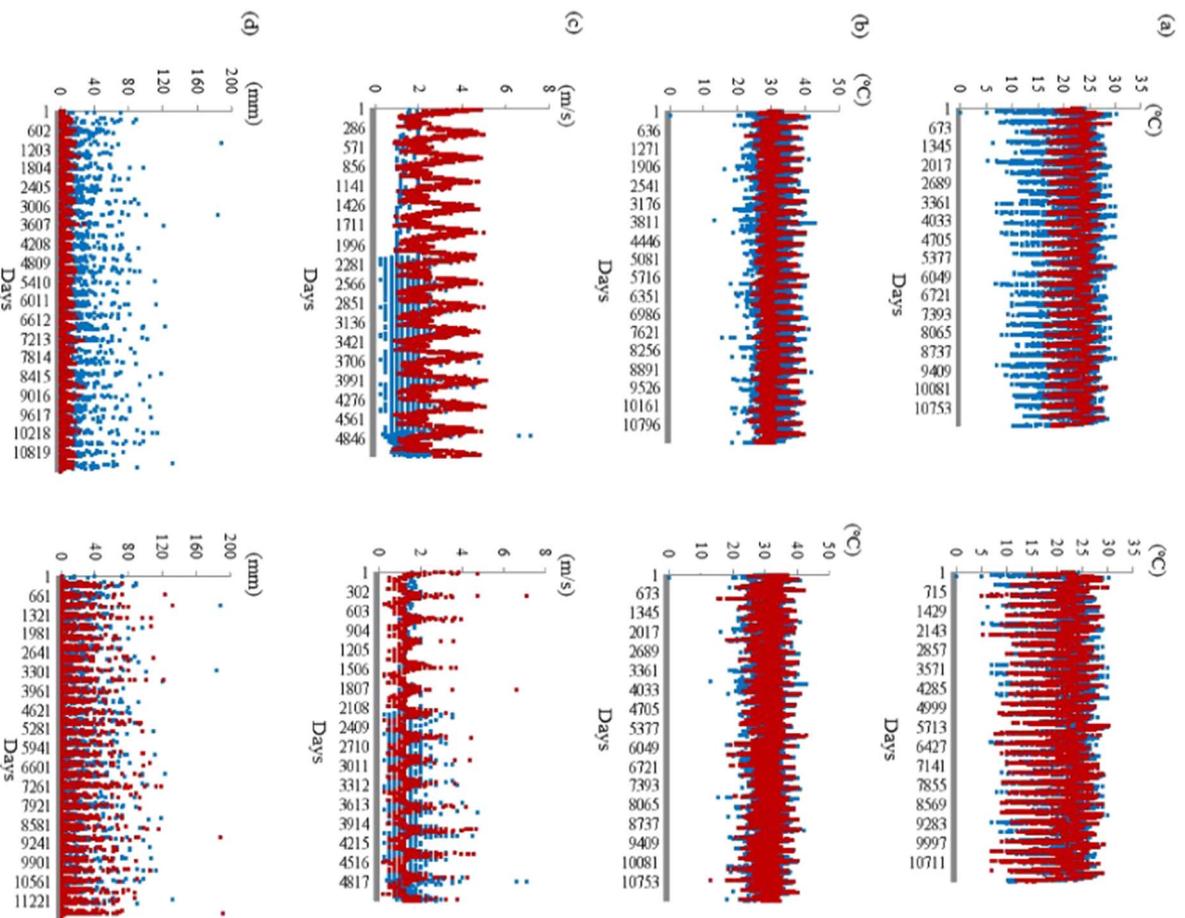


Fig. 2. Comparison of observed weather data (blue dots) to SINTEX-F outputs (red dots in the figures on the left side) and CDFDM outputs (red dots in the figures on the right side) against observed weather data (blue dots) for Savannakhet: (a) minimum temperature, (b) maximum temperature, (c) wind speed, and (d) rainfall. X axis shows the number of days for the run from October 1, 1982. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Mean error (ME) for Indonesia and Lao PDR in daily rainfall (RF), minimum and maximum air temperature (T_{min} , T_{max}), wind speed (WS). Obs: Observed data, CDFDM: CDFDM outputs, SINTEX-F: SINTEX-F outputs.

	RF	T_{min}	T_{max}	WS
Indonesia (Central Java)				
ME (Obs-SINTEX-F)	1.13	3.55	−3.08	2.90
ME (Obs-CDFDM)	−1.00	−0.74	0.04	0.13
Lao PDR (Savannakhet)				
ME (Obs-SINTEX-F)	−0.36	1.93	−0.92	1.41
ME (Obs-CDFDM)	−0.25	0.50	−0.10	0.43

3.2. Applicability of the seasonal climate predictions in grain yield prediction

Fig. 5 shows the rainfall distribution and total amount during the experimental period from 2012 to 2014. According to the historical data, exceedance probability was 0.82, 0.75, 0.06 and 0.13 for the total rainfall of late rainy season 2012, early rainy season 2012–2013, late rainy season 2013 and early rainy season 2013–2014, respectively. This means that on-station field experiments for the first two seasons and

another two seasons were carried out in slightly drier and very wetter conditions, respectively, than in normal years.

Fig. 6 shows the results of grain yield and straw production from Exp-1. Grain yield for Chherang was higher than for IR64 for late rainy season 2012 and early rainy season 2012–2013 when nitrogen was applied at a rate of 60 and 120 kg ha^{−1} and this indicates a grain yield increase with fertilization. Grain yield of IR64 for the same period decreased along with the increase in fertilizer dosage and this is due to some damage by diseases such as neck blast (data not shown). Despite the diseases, a substantial yield loss was not observed for Chherang during two seasons. On the other hand, grain yield for late rainy season 2013–2014 was comparatively lower than that of the previous two seasons. This season was recognized as a wetter season than a normal year; hence, the growth environment for the rice plant could be less suitable in terms of solar radiation.

Table 3 summarizes the ANOVA test in grain yield and straw production for all seasons through Exp-1. According to the results, fertilizer application showed a significant difference at the level of 0.1% for grain yield and straw production for all seasons. Water management showed a significant difference at the level of 5% for grain yield and straw production for the first two seasons but there was no significant

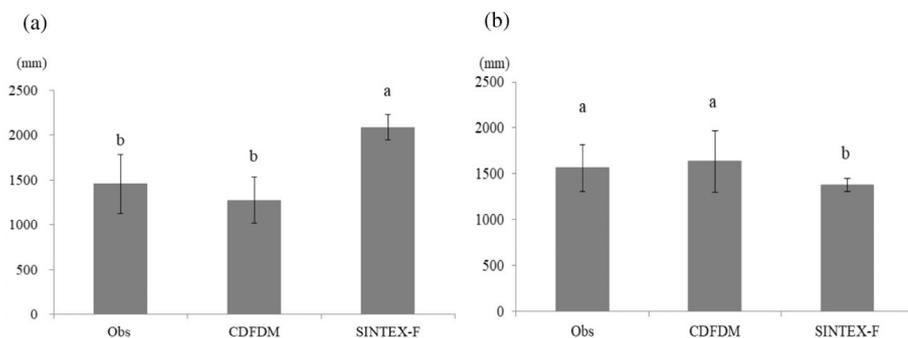


Fig. 3. Comparison of mean annual rainfall for (a) Central Java and (b) Savannakhet. Different alphabet letters mean a significant different at 5% by Tukey. Obs: observed weather data, CDFDM: CDFDM outputs, SINTEX-F: SINTEX-F outputs.

Table 2
Performance of predictability on mean annual rainfall by SINTEX-F and CDFDM against Observed data for the study sites. CDFDM: CDFDM outputs, SINTEX-F: SINTEX-F outputs.

Site	Year	Observed	CDFDM	SINTEX-F
Rainfall (mm)				
Central Java	RF below normal ($P > 0.80$)			
	2001	1031	1010	1975
	2004	1150	1053	1843
	2012	1147	1228	2192
	RF above normal ($P < 0.20$)			
	1999	1894	984	2131
	2010	2330	1749	2229
2013	1699	1166	1989	
Savannakhet	RF below normal ($P > 0.80$)			
	2003	1199	1469	1313
	2009	1295	1642	1389
	2012	1035	1892	1397
	RF above normal ($P < 0.20$)			
	2001	1920	1409	1312
	2002	1982	2684	1561
2005	1768	1767	1312	

difference for late rainy season 2013. Varietal difference showed the same result as for the fertilizer treatment except late rainy season 2013. Interaction between fertilizer application and varietal difference showed a significant difference at the level of 0.1% for grain yield and straw production in the first two seasons, 5% grain yield in late rainy season 2013 but no significance in straw production for late rainy season 2013. Interaction of water management with fertilizer application, varietal difference, and those two treatments was not significantly different.

Fig. 7 shows the results of grain yield for Exp-2 as a function of different sowing dates. During the experiment of Exp-2, the total rainfall was below normal for the early season 2012–2013, above normal for the late rainy season 2013 and the early rainy season 2013–2014. However, the grain yield varied according to the sowing timing regardless the rainfall amount. Significant difference on grain yield was found in sowing timing except the one for IR64 in early rainy season

2012–2013 and Ciherang in early rainy season 2013–2014. Nevertheless, the results for these seasons also showed similar trend as being observed in other seasons.

A simulated grain yield was obtained through ORYZA with crop data from Exp-1 and compared with actual grain yield obtained from Exp-2 in order to evaluate the performance of the grain yield simulation of the model through a comparison of simulated grain yields with measured ones as function of different sowing dates. The results are shown in Fig. 8. The slope and intercept for the graph of Ciherang are close to 1 and 0, respectively, and RMSEn was 16.4%. Those for IR64 are also similar and RMSEn was 13.4%. According to these results, ORYZA with datasets from Exp-1 was able to simulate adequately the grain yield for different varieties as a function of different sowing dates.

The results obtained from the grain yield simulation were further used to test the applicability of the seasonal climate predictions for grain yield predictions. Fig. 9 shows the results of field validation of grain yield predictions produced through ORYZA with the bias-reduced seasonal climate predictions. In early rainy season 2013, rainfall occurred early in October and cumulative rainfall reached > 30 mm, which motivated farmers to start sowing. The first sowing dates of farmers for IR64 and Ciherang were 6 and 10 October, respectively. The mean value in grain yield obtained through the farmers' practice was $0.67 \pm 0.38 \text{ t ha}^{-1}$ for IR64 and $1.65 \pm 0.47 \text{ t ha}^{-1}$ for Ciherang. On the other hand, grain yield obtained through field validation and yield prediction during the same period was $4.13 \pm 0.37 \text{ t ha}^{-1}$ for IR64 and $4.25 \pm 0.41 \text{ t ha}^{-1}$ for Ciherang and $4.46 \pm 0.21 \text{ t ha}^{-1}$ for IR64 and $4.04 \pm 0.11 \text{ t ha}^{-1}$ for Ciherang, respectively. The RMSEn for IR64 and Ciherang was 10.33% and 8.93%, respectively. The field validation was continued in late rainy season 2014 for the grain yield predictions of Ciherang and predicted grain yields were $2.32 \pm 0.44 \text{ t ha}^{-1}$ and $2.49 \pm 0.86 \text{ t ha}^{-1}$, respectively, and the RMSEn was 29.92%. Obtained RMSEn shows that grain yield predictions were excellent for Ciherang and good for IR64 in the early rainy season and fair for Ciherang in the late rainy season. These results proved the adequate performance of grain yield predictions through the application of seasonal climate predictions. The discrepancy in grain yield between the farmers' practice and field validation could be attributed to the difference in sowing timing and fertilizer application

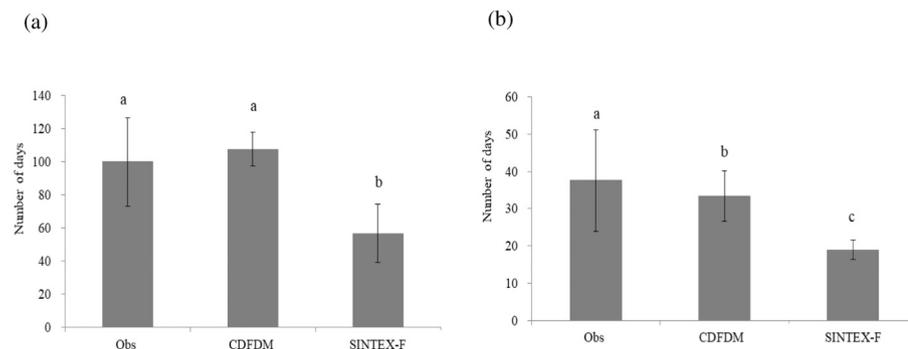


Fig. 4. Mean number of days to accumulate (a) 139 mm for Central Java and (b) 72 mm for Savannakhet during the rainy season. Different alphabet letters mean a significant difference at 5% by Tukey. Obs: observed weather data, CDFDM: CDFDM outputs, SINTEX-F: SINTEX-F outputs.

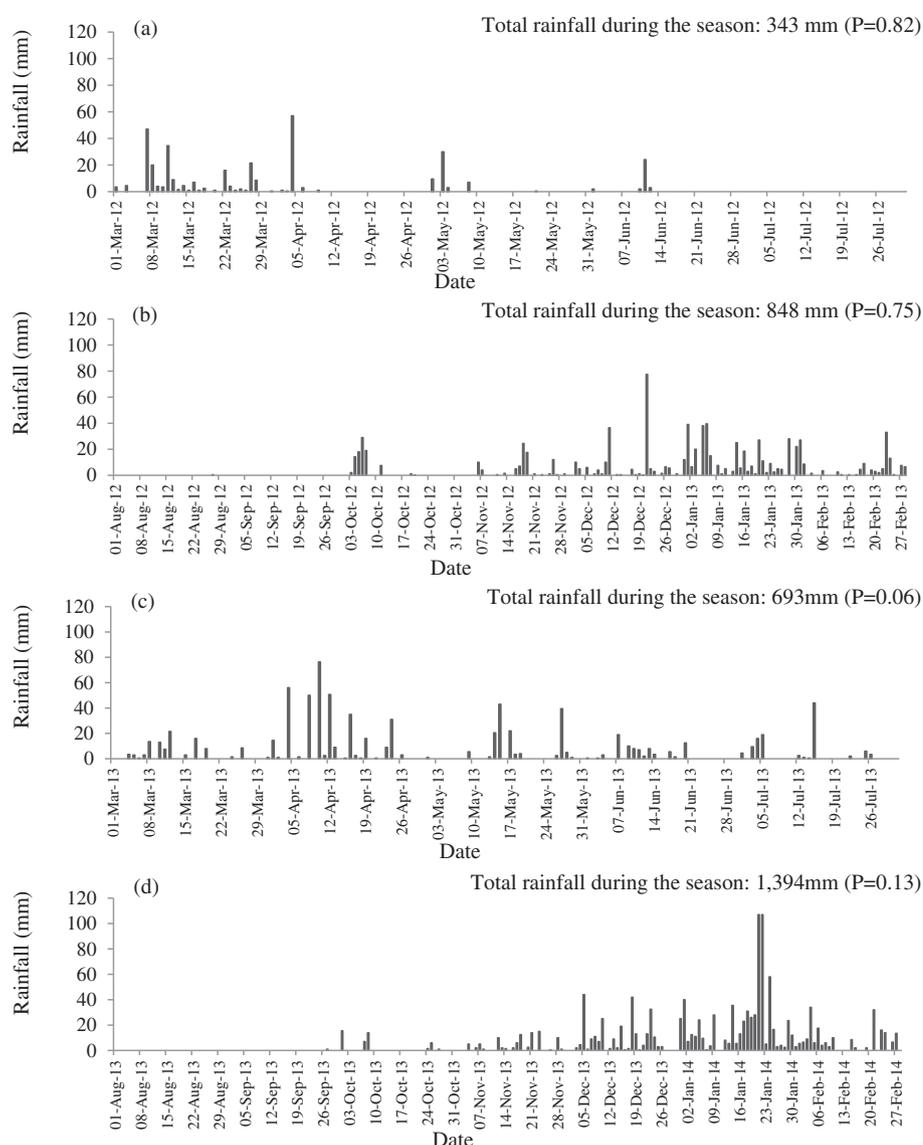


Fig. 5. Daily rainfall during experiment in Central Java for (a) late rainy season 2012, (b) early rainy season 2012–2013, (c) late rainy season 2013, and (d) early rainy season 2013–2014. P means the exceedance probability.

practice. Local farmers in the surveyed area usually apply inorganic fertilizer only one time at basal, which is around 40 days after sowing. This was the same during the early rainy season 2012–2013 and farmers followed their usual practice. In the case of the late rainy season, grain yield obtained through the farmers' practice was close to the predicted grain yield but the timing was much later and coincided with the yield depletion period.

4. Discussion

Optimum timing for sowing is crucial to obtain higher grain yield as the results of our study showed. This also coincides with the results of [Basnayake et al. \(2006\)](#) that lowland rice in Lao PDR had lower grain yield as sowing timing was not taking place appropriately. These results indicate that grain yield reduction due to the effect of sowing timing is a common problem across Southeast Asia regardless of latitude. [Tuong et al. \(2000\)](#) showed that drought stresses between panicle initiation and flowering reduced final grain yield significantly but stresses during the vegetative stage didn't reduce total biomass at harvest. On the other hand, short-maturity varieties whose flowering coincided with the period of peak rainfall had lower grain yield due to early sowing ([Basnayake et al., 2006](#)). This implies that an optimum sowing timing

plays a crucial role in rainfed rice production not only because of good plant establishment, but also because of an escape mechanism for late-season abiotic stresses such as drought and flood. Most local rainfed rice farmers usually use their empirical knowledge or their traditional cropping calendar to decide sowing timing ([Boling et al., 2016](#)). Our field experiment in the early rainy season found different sowing dates among farmers and this implies that local farmers tend to use their empirical decision making for sowing timing instead of using a common decision tool such as a traditional cropping calendar. Despite the wide range of sowing dates, grain yield from farmers' fields was much lower than that from our field experiments, which was around 4 t ha^{-1} . The potential grain yield of Ciherang and IR64 is $5\text{--}7 \text{ t ha}^{-1}$ and 6 t ha^{-1} , respectively ([Balai Besar Penelitian Padi \(BP Padi\), 2015](#)), and on-farm testing showed that grain yield can be close to this level through an optimum timing for sowing even under field conditions.

The discrepancy obtained in grain yield could also be attributed to the nutrient management between the experiments and the farmers' practice. [Boling et al. \(2016\)](#) found that farmers in Central Java practiced only one-time fertilizer application at basal. Usually, fertilizer should be split a few times and applied along critical crop growth stages such as maximum tillering and panicle initiation. According to a study by [Peng et al. \(1996\)](#), the application of nitrogen fertilizer at the panicle

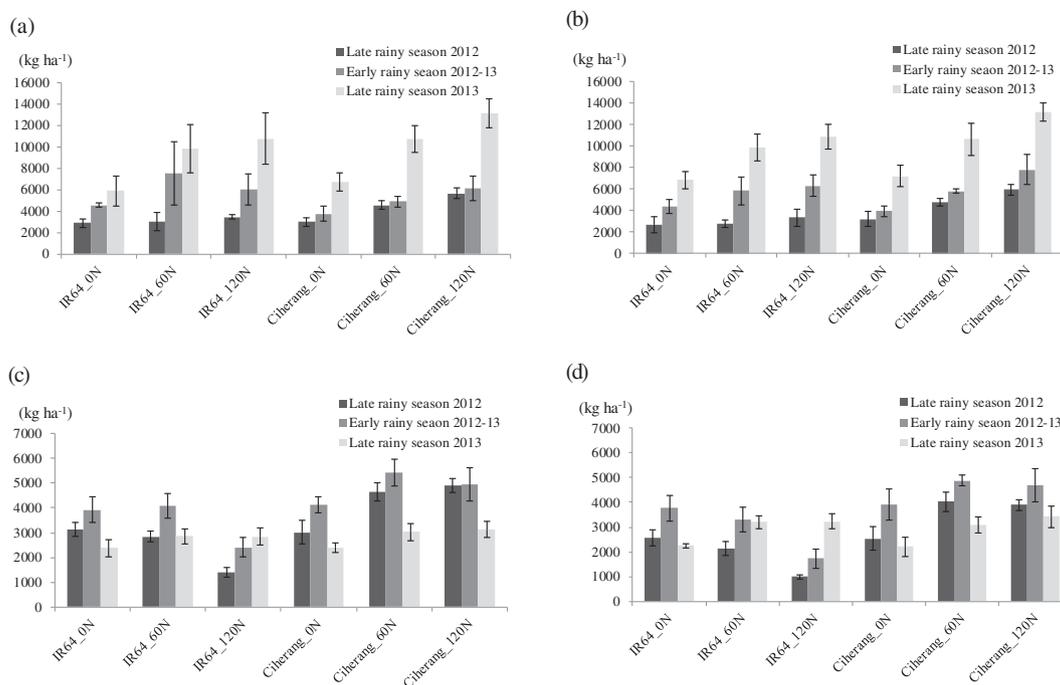


Fig. 6. Seasonal variations in Exp-1 for (a) straw production in irrigated, (b) straw production in rainfed, (c) grain yield production in irrigated, and (d) grain yield production in rainfed.

initiation stage increased grain yield significantly due to increased nutrient-use efficiency by the rice plant. However, applying fertilizer at the right timing is not an easy practice because each variety has its own phenology and crop growth stages could also vary according to the abiotic stresses during the cropping period (Tuong et al., 2000).

In order to predict crop growth and grain yield according to the changes and variation in local weather in rainfed areas, using a crop growth model like ORYZA is an effective strategy because of its skill to simulate agroecological rice growth processes by daily weather data as inputs (Bouman et al., 2001). This means growth conditions at critical stages like panicle initiation and flowering stages can be predictable by ORYZA to avoid abiotic stresses such as drought when daily weather predictions can be available for crop growth simulation. In this study, the predictive accuracy and applicability of SINTEX-F were evaluated because SINTEX-F has a high performance for the prediction of ENSO and is considered to be advantageous for the countries like Indonesia where Asian monsoon is key phenomenon in rainfed areas. Obtained results showed a discrepancy between observed weather data and SINTEX-F because of the existing bias. This bias was removed through CDFDM and less-bias weather predictions were obtained for crop growth and grain yield predictions to be tested through field experiment. The results obtained from the field experiment showed a

feasibility of improving attainable grain yield by implementing optimum timing for sowing, which can be driven by the seasonal climate predictions-based ORYZA simulation. Seasonal climate predictions can't be directly used for crop growth model hence CDFDM, that is a suitable statistical model to flexibly downscale daily weather data (Iizumi et al., 2011), was applied for ORYZA that requires daily rainfall, maximum and minimum air temperature, wind speed, vapor pressure and solar radiation for crop growth and development. Furthermore, CDFDM is a simple and less costly statistical model (Iizumi et al., 2011), it is useful for the widely application of the method in rainfed areas. However, it has a limitation in orographic precipitation, using the high-resolution (0.05° × 0.05°) daily precipitation data or a sophisticated special interpolation method should be considered in order to improve the representation of the geographical pattern for the parameters derived from CDFDM (Iizumi et al., 2011).

The rainy season in 2013 had a certain amount of rainfall in early October and the sowing timing for farmers' fields coincided with this period. In general, sowing for dry seeding is done after several rainfall events to have enough moisture for seed germination. The practice of rainfed rice farmers in Central Java was the same and they usually wait for certain numbers of rainfall events to make the soil moist enough. This is the local risk management to avoid a water shortage at the

Table 3
Variability of grain yield in different seasons of (a) straw and (b) grain yield as affected by water management (W), fertilizer dosage (F), variety (V), and their interactions.

	Water (W)	Fertilizer (F)	W × F	Variety (V)	W × V	F × V	W × F × V
(a) Straw (kg ha⁻¹)							
Late rainy season 2012	ns*	***	ns	***	ns	***	ns
Early rainy season 2012–2013	ns	***	ns	***	ns	**	ns
Late rainy season 2013	ns	***	ns	ns	ns	ns	ns
(b) Grain yield (kg ha⁻¹)							
Late rainy season 2012	**	***	ns	***	ns	***	ns
Early rainy season 2012–2013	ns	***	ns	***	ns	***	ns
Late rainy season 2013	ns	***	ns	***	ns	**	ns

ns = not significant.

* Significant at 5% level.

** Significant at 1% level.

*** Significant at 0.1% level.

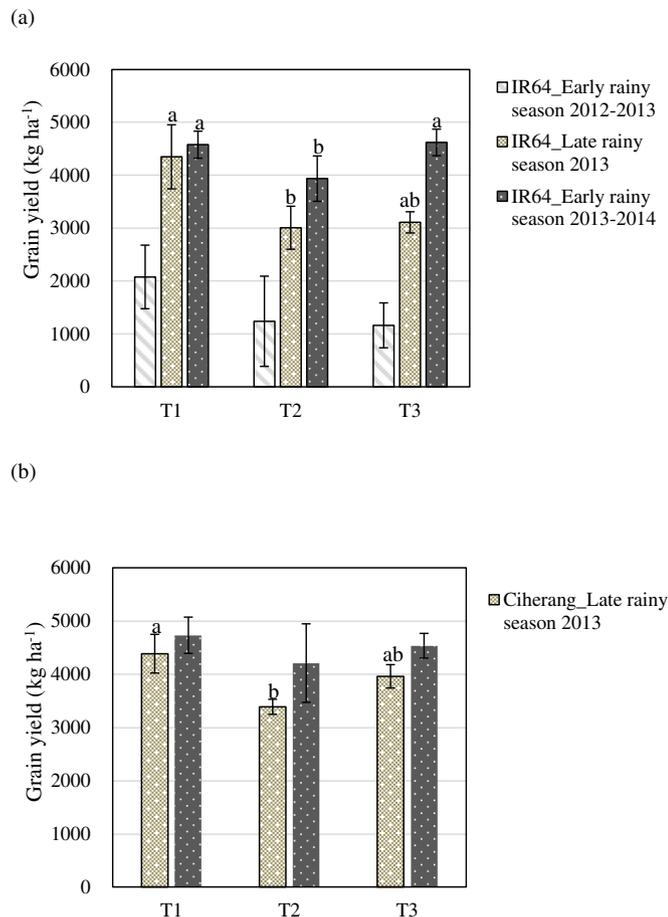


Fig. 7. Grain yield of (a) IR64 and (b) Ciherang in Exp-2 for various seasons as function of different sowing dates. Different alphabet means a significant different at 5% within the season by Tukey.

earlier stage of seedlings. However, the farmers experienced a month-long water shortage after sowing in early October. Rice is very sensitive to water stress, especially young seedlings (Fischer and Fukai, 2003; Murty and Ramakrishnayya, 1982). When seedlings are exposed to a water shortage for a certain period, this could cause substantial damage, which entails a significant grain yield loss or requires farmers to re-sowing. This delays growth and reduces the efficiency in water and

nutrient use in rainfed rice production. Using seasonal climate predictions in a crop growth model, it was possible to determine the optimum timing for sowing that permitted avoiding risk of water shortage in the establishment stage, and this resulted in much higher grain yield than the yield from farmers' practices. Some numbers of farmers started sowing around same period with the optimum timing but their grain yield was as low as the one without nitrogen fertilizer application. As Boling indicated (2016), farmers' practice in study area is different from the recommended fertilizer management and this results an inefficient fertilizer use for rice growth. This implies that the seasonal climate predictions-based ORYZA simulation was able to serve rainfed rice farming for the appropriate decision making to minimize the risks and optimize the production.

5. Conclusions

Rainfed rice farming has low yield. This is due to high uncertainties in terms of the start and end of the rainy season, rainfall amount and duration, and low nutrient-use efficiency. In addition, climate variabilities and extremes are more often and amplified than before but rainfed rice farmers have few ways to cope with this change due to lack of tools and information. Optimum sowing is essential to improve grain yield and a prediction is considered as a key tool for this to be possible. The study tested seasonal climate predictions for its predictive accuracy and its applicability with a crop growth model for the prediction of rice growth and its grain yield in selected rainfed areas. According to the results obtained, seasonal climate predictions at a global scale can be applied to specific areas through CDFDM and this information can be used to identify an optimum timing for rice growth and its grain yield predictions by ORYZA. The study focused on selected rainfed areas in Southeast Asia; hence, the applicability of the results obtained is limited. Testing the results obtained in wider areas is imperative to benefit rainfed rice farmers in the region. Furthermore, using the high-resolution daily precipitation data or a sophisticated special interpolation method should be considered in order to improve the representation of the geographical pattern for the parameters derived from CDFDM.

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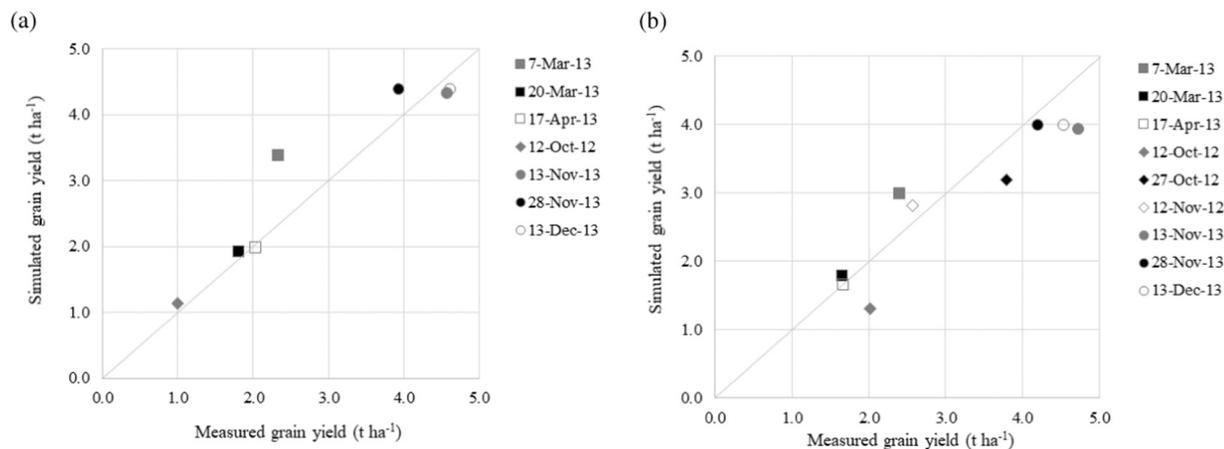


Fig. 8. Evaluation on the model fit of simulated grain yield for (a) IR64 and (b) Ciherang. Applied fertilizer for each sowing date was 120N, 22P, 90K, 5Zn kg ha⁻¹.

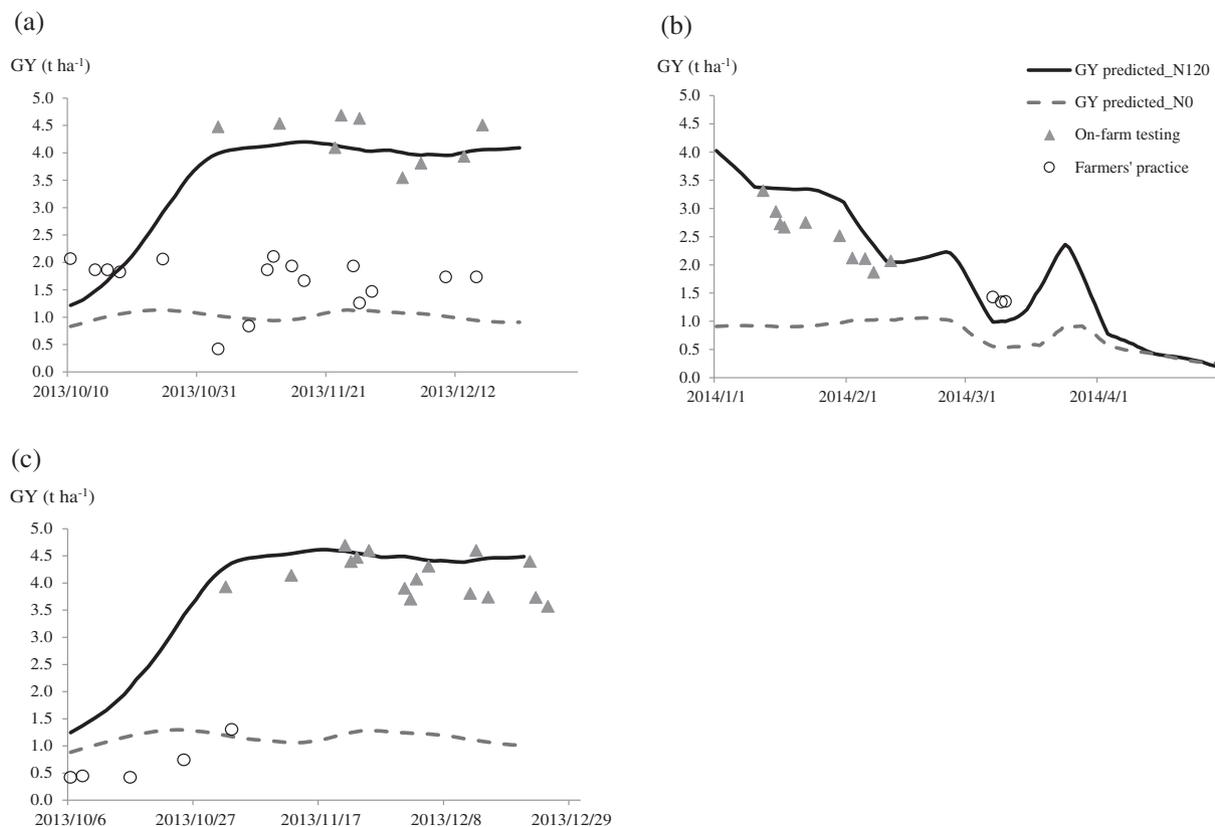


Fig. 9. Comparison of grain yield of on-farm testing (solid triangles) and surrounding farmers (hollow circles) with yield predictions by seasonal climate predictions based on ORYZA simulation with nitrogen application (solid line) and no nitrogen application (broken line) for (a) Ciherang in early rainy season 2013–2014, (b) Ciherang in late rainy season, and (c) IR64 in early rainy season 2013–2014.

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References

Abdullah, P.S., 1998. Risk and the value of rainfall prediction for rainfed rice in the Philippines. *Philipp. J. Crop Sci.* 23 (3), 159–165.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration. In: Guidelines for computing crop water requirements. United Nations, FAO, Rome Irrig. & Drain. Paper No. 56.

Amien, I., Las, I., 2000. Biophysical characterization of rainfed system in Java and South Sulawesi and implications for research. In: Tuong, T.P., Kam, S.P., Wade, L., Pandey, S., Bouman, B.A.M., Hardy, B. (Eds.), *Characterizing Rainfed Environments. Proceedings of the International Workshop on Characterizing and Understanding Rainfed Environments*. International Rice Research Institute, Los Baños (Philippines), pp. 145–155.

Balai Besar Peneltian Padi (BP Padi), 2015. Deskripsi Varietas Unggul Baru Padi.

Basnayake, J., Fukai, S., Sipaseuth, Monthathip, C., 2006. Advances in agronomic research in the lowland rice environments of Laos. In: Schiller, J.M., Schiller, J.M., Chanphengxay, M.B., Linquist, B., Appa Rao, S. (Eds.), *Rice in Laos*. International Rice Research Institute, Los Baños (Philippines), pp. 349–368.

Boling, A., Tuong, T.P., Jatmiko, S.Y., Burac, M.A., 2004. Yield constraints of rainfed lowland rice in Central Java, Indonesia. *Field Crop Res.* 90, 351–360.

Boling, A.A., Tuong, T.P., Suganda, H., Konboon, Y., Harnpichitvitaya, D., Bouman, B.A.M., Franco, D.T., 2008. The effect of toposquence position on soil properties, hydrology, and yield of rainfed lowland rice in Southeast Asia. *Field Crop Res.* 106, 22–33.

Boling, A.A., Hermawan, A., Komalawati, L., Hayashi, K., 2016. An assessment of small-scale rice farmers' adaptability to climate change: case study in Central Java, Indonesia. *Asian J. Agric. Extent. Econ. Sociol.* 10 (3), 1–13.

Bouman, B.A.M., van Laar, H.H., 2006. Description and evaluation of the rice growth model ORYZA2000 under nitrogen-limited conditions. *Agric. Syst.* 87, 249–273.

Bouman, B.A.M., Kropff, M.J., Tuong, T.P., Wopereis, M.C.S., ten Berge, H.F.M., van Laar, H.H., 2001. ORYZA2000: Modeling lowland rice. International Rice Research Institute, Wageningen (Wageningen University and Research Centre, Los Baños (Philippines)).

Bristow, K.L., Campbell, G.S., 1984. On the relationship between incoming solar radiation and daily maximum and minimum temperature. *Agric. For. Meteorol.* 31, 159–166.

Cantelaube, P., Terres, J.M., 2005. Seasonal weather predictions for crop yield modelling in Europe. *Tellus* 57A, 476–487.

Dobermann, A., Fairhurst, T., 2000. *Rice: Nutrient Disorders & Nutrient Management*. Handbook series. Potash & Phosphate Institute (PPI), Potash & Phosphate Institute of Canada (PPIC), and International Rice Research Institute (IRRI).

Fayed, T.B., El-Sarag, E., Hassanein, M.K., Magdy, A., 2015. Evaluation and prediction of some wheat cultivars' productivity in relation to different sowing dates under North Sinai region conditions. *Ann. Agric. Sci.* 60 (1), 11–20.

Fischer, K.S., Fukai, S., 2003. How rice responds to drought. In: Fischer, K.S., Lafitte, R., Fukai, S., Atlin, G., Hardy, B. (Eds.), *Breeding Rice for Drought-Prone Environments*. International Rice Research Institute, Los Baños (Philippines), pp. 32–36.

Fukai, S., 1999. Phenology in rainfed lowland rice. *Field Crop Res.* 64, 51–60.

Goswami, B.N., Xavier, P.K., 2005. ENSO control on the South Asian monsoon through the length of the rainy season. *Geophys. Res. Lett.* 32, L18717. <http://dx.doi.org/10.1029/2005GL023216>.

GRiSP (Global Rice Science Partnership), 2013. *Rice Almanac*, 4th edition. International Rice Research Institute, Los Baños (Philippines).

Hansen, J.W., Mishra, A., Rao, K.P.C., Indeje, M., Ngugi, R.K., 2009. Potential value of GCM-based seasonal rainfall forecasts for maize management in semi-arid Kenya. *Agric. Syst.* 101, 80–90.

Iizumi, T., Nishimori, M., Ishigooka, Y., Yokozawa, M., 2010. Introduction to climate change scenario derived by statistical downscaling (in Japanese). *J. Agric. Meteorol.* 66, 131–143. <http://dx.doi.org/10.2480/agrmet.66.2.5>.

Iizumi, T., Nishimori, M., Dairaku, K., Adachi, S.A., Yokozawa, M., 2011. Evaluation and intercomparison of downscaled daily precipitation indices over Japan in present-day climate: strengths and weaknesses of dynamical and bias correction-type statistical downscaling methods. *J. Geophys. Res.* 116, D01111. <http://dx.doi.org/10.1029/2010JD014513>.

Iizumi, T., Takayabu, I., Dairaku, K., Kusaka, H., Nishimori, M., Sakurai, Gen, Ishizaki, N., Adachi, S.A., 2012. Future change of daily precipitation indices in Japan: a stochastic weather generator-based bootstrap approach to provide probabilistic climate information. *J. Geophys. Res.* 117, D01114. <http://dx.doi.org/10.1029/2011JD017197>.

- Ines, A.V.M., Hansen, J.W., 2006. Bias correction of daily GCM rainfall for crop simulation studies. *Agric. For. Meteorol.* 138, 44–53.
- IPCC, 2014. Climate change 2014: synthesis report. In: Team, Core Writing, Pachauri, R.K., Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland.
- IRRI, 2014. STAR, Version 2.0.1. Biometrics and Breeding Informatics, PBGB Division, International Rice Research Institute, Los Baños (Philippines).
- Jamieson, P.D., Porter, J.R., Wilson, D.R., 1991. A test of the computer simulation model ARCWHEAT 1 on wheat crops grown in New Zealand. *Field Crop Res.* 27, 337–350.
- Lansigan, F.P., de los Santos, W.L., Coladilla, J.O., 2000. Agronomic impacts of climate variability on rice production in the Philippines. *Agric. Ecosyst. Environ.* 82, 129–137.
- Linquist, B., Sengxua, P., 2001. Nutrient Management of Rainfed Lowland Rice in the Lao PDR. International Rice Research Institute, Los Baños (Philippines).
- Loague, K., Green, R.E., 1991. Statistical and graphical methods for evaluating solute transport model: overview and application. *J. Contam. Hydrol.* 7, 51–73.
- Luo, J.-J., Masson, S., Behera, S.K., Yamagata, T., 2008. Extended ENSO predictions using a fully coupled ocean–atmosphere model. *J. Clim.* 21, 84–93.
- Mackill, D.J., Coffman, W.R., Garrity, D.P., 1996. Rainfed Lowland Rice Improvement. International Rice Research Institute, Los Baños (Philippines).
- Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H., Luo, J.J., 2014. Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorol. Appl.* 21, 733–742.
- Marletto, V., Ventura, F., Fontana, G., Tomei, F., 2007. Wheat growth simulation and yield prediction with seasonal predictions and a numerical model. *Agric. For. Meteorol.* 147, 71–79.
- Meza, F.J., Hansen, J.W., Osgood, D., 2008. Economic value of seasonal climate forecasts for agriculture: review of ex-ante assessments and recommendations for future research. *J. Appl. Meteorol. Climatol.* 47, 1269–1286.
- Murty, K.S., Ramakrishnayya, G., 1982. Shoot characteristics of rice for drought resistance. In: *Drought Resistance in Crops with Emphasis on Rice*. International Rice Research Institute, Los Baños (Philippines), pp. 14–152.
- Peng, S., Garcia, F.V., Laza, R.C., Sanico, A.L., Visperas, R.M., Cassman, K.G., 1996. Increased N-use efficiency using a chlorophyll meter on high-yielding irrigated rice. *Field Crop Res.* 47, 243–252.
- Rosenberg, N.J., Blad, B.L., Verma, S.B., 1983. *Microclimate: The Biological Environment*. John Wiley & Sons, New York.
- Roudier, P., Sultan, B., Quirion, P., Baron, C., Alhassane, A., Traoré, S.B., Muller, B., 2012. An *ex-ante* evaluation of the use of seasonal climate forecasts for millet growers in SW Niger. *Int. J. Climatol.* 32, 759–771.
- Schiller, J.M., Chanphengxay, M.B., Linquist, B., Appa Rao, S. (Eds.), 2006. *Rice in Laos*. International Rice Research Institute, Los Baños (Philippines).
- Semenov, M.A., Doblas-Reyes, F.J., 2007. Utility of dynamical seasonal predictions in predicting crop yield. *Clim. Res.* 34, 71–81.
- Tuong, T.P., Singh, A.K., Siopongco, J.D.L.C., Wade, L.J., 2000. Constraints to high yield of dry-seeded rice in the rainy season of a humid tropic environment. *Plant Prod. Sci.* 3 (2), 164–172.
- Walther, B.A., Moore, J.L., 2005. The concepts of bias, precision and accuracy, and their use in testing the performance of species estimators, with a literature review of estimator performance. *Ecography* 28, 815–829.
- Wassmann, R., Jagadish, S.V.K., Heuer, S., Ismail, A., Redona, E., Serraj, R., Singh, R.K., Howell, G., Pathak, H., Sumfleth, K., 2009. Climate change affecting rice production: the physiological and agronomic basis for possible adaptation strategies. In: Donald, L., Sparks, D.L. (Eds.), *Advances in Agronomy*. Vol 101. Academic Press, Burlington, pp. 59–122.
- Wihardjaka, A., Kirk, G.J.D., Abdulrachman, S., Mamaril, C.P., 1999. Potassium balances in rainfed lowland rice on a light-texture soil. *Field Crop Res.* 64, 237–247.