


Sustaining rice productivity through weather-resilient agricultural practices

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Abstract

BACKGROUND: Enhancing productivity and profitability and reducing climatic risk are the major challenges for sustaining rice production. Extreme weather can have significant and varied effects on crops, influencing agricultural productivity, crop yields and food security.

RESULTS: In this study, a comparative evaluation of two crop management systems was performed involving farmers adopting a weather forecast-based advisory service (WFBAS) and usual farmers' practice (FP). WFBAS crop management followed the generated weather forecast-based advice whereas the control farmers (FP) did not receive any weather forecast-based advice, rather following their usual rice cultivation practices. The results of the experiments revealed that WFBAS farmers had a significant yield advantage over FP farmers. With the WFBAS technology, the farmers used inputs judiciously, utilized the benefit of favorable weather and minimized the risk resulting from extreme weather events. As a result, besides the yield enhancement, WFBAS provided a scope to protect the environment with the minimum residual effect of fertilizer and pesticides. It also reduced the pressure on groundwater by ensuring efficient water management. Finally, the farmers benefited from higher income through yield enhancement, reduction of the costs of production and reduction of risk.

CONCLUSION: A successful and extensive implementation of WFBAS in the rice production system would assist Bangladesh in achieving Sustainable Development Goal 2.4, which focuses on rice productivity and profitability of farmers as well as long-term food security of the country.

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Supporting information may be found in the online version of this article.

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INTRODUCTION

Bangladesh is mostly an agrarian country in which the agricultural sector plays a vital role in promoting economic growth. The contributions of agriculture and the crop subsector to the gross domestic product (GDP) are about 13.47% and 6.77%, respectively. Rice is the main staple crop in Bangladesh, supplying more than 80% of the total consumed food and contributing 60% of the total required protein. The country ranks third in the world for rice production.¹ The contribution of the crop subsector to the agricultural GDP is dominated by rice, with a share of about 70%.² Nearly 48% of total rural employments in Bangladesh are directly or indirectly involved in rice production for their livelihood, and more than 13 million farms grow rice in an area covering some 11.77 million hectares, accounting for 78% of the total cropped area.³

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The weather significantly influences crop growth, maturity, yields, pest and disease prevalence, and water and fertilizer needs.⁴ Furthermore, the weather also has an impact on the quality of crops during movement from field to warehousing and then to market.⁵ Adverse weather can affect the quality of products during transportation, as well as the viability and vigor of seeds and planting material during warehousing.⁶ Crops and cropping systems must be matched to the meteorological requirements for maximum yield at a specific area, and pest- and disease-prevalent seasons must be avoided. Short-period meteorological data, either routine or analyzed (like initial and conditional probability), play a significant role in strategic crop and cropping practice planning.⁷

In Bangladesh, the population is on an increasing trend, so the demand for rice is also increasing. In sustaining the flow of food production, swelling climate vulnerability and reducing agricultural resources seem to be the greatest challenges.⁸ In spite of the established implications of adverse weather events and rising anxiety about the future of agriculture, weather and climate risk moderation appear to be absent in agricultural development approaches. This reflects a gradual acceptance of climate as a part of the environment, but never as a source of management opportunities.

National and international policies are designed to address the risk of extreme weather events and establish climate-resilient agriculture through better crop management. The Sustainable Development Goal's Zero Hunger has set a target by 2030 to double agricultural productivity in a sustainable manner through implementing resilient agricultural activities that enhance productivity and production, thereby aiding ecosystem sustainability and strengthening its capacity to adapt to climate change, extreme weather, droughts, floods and other disasters.⁹ Through rigorous, adaptive and integrated strategies, the Bangladesh Delta Plan 2100 aims to confirm long-term water and food security, economic growth and environmental sustainability, as well as significantly lowering the risk of chronic diseases and increasing climate resilience and other challenges.¹⁰ Bangladesh's national agricultural policy 2018 and its extension 2020 prioritize weather-smart agricultural practices by implementing an early warning system for effectively forecasting extreme climatic events and delivering action-oriented advice to farmers that will help to reduce the damage caused by natural disasters.¹¹

Usually, farmers cultivate in a weather-blind situation for subsequent hours. Therefore, variations in weather and weather extreme events frequently damage crops, and farmers do not take any precautionary measures.^{12,13} Moreover, the benefit of favorable weather events (e.g. fertilizer application on a sunny day or reduction of irrigation for the next hours/days of rainfall) remains unexploited. Weather-smart farming would consider the weather forecast and translate it into advice for farm operations to reduce the risk of adverse weather events and utilize the benefit of favorable weather events.

Agricultural weather forecasts give the required meteorological messages to guide farmers in making decisions in time about particular field activities. The impact of weather irregularities on a given crop depends on different cropping stages and on the location.¹⁴ Weather forecast-based advice service (WFBAS) developed by Bangladesh Rice Research Institute (BRRI) is a crop management system that uses weather forecasts to generate location-specific and crop growth stage-wise advisory services. WFBAS is an effective concept and technique for weather as well as climate-smart rice production in Bangladesh. Because of this,

farmers and decision-makers will be able to make appropriate rice crop management decisions for various weather conditions ahead of time. It would lessen risk as well as allow farmers to take advantage of favorable weather circumstances. However, the performance and effectiveness of the system are still unexplored. It is important to figure out the effectiveness and impact of WFBAS in addressing extreme weather events and utilizing the benefit of favorable weather for enhancing rice productivity in Bangladesh. Thus, the main aim of the study reported here was to compare the performance of WFBAS and current farmers' practices (FP) regarding yield enhancement, profitability and risk of rice cultivation in different regions of Bangladesh.

MATERIALS AND METHODS

Target environments

In Bangladesh, rice is grown in three overlapping seasons, i.e. winter rice (Boro), which is mostly irrigated (temperature, evaporative demand and solar radiation are high and relative humidity and disease pressure are low), rainfed upland rice (Aus) and monsoon rice (transplanted Aman). In this study, we conducted experiments in the winter season through farmers' participation. We expected the best response of the tested treatments in the winter season, which is crucial for national food security in terms of gross production in Bangladesh. The intensity of winter severely affects seedlings and later plant growth. Winter rice mainly depends on irrigation but it is frequently affected by early flash floods and heavy rainfall. In 2020–2021, the total production of rice in Bangladesh was 39.18 million tons, of which winter rice accounted for 53.32%.³ Therefore, testing the performance of WFBAS in the winter season promised to generate the best evidence of its weather resilience.

Experimental sites

Two crop management systems were established at five locations in Bangladesh in the winter rice season of 2019–2020 and 2020–2021. At each location, two farmers' fields with an area of 0.13 ha for each crop management system (one under FP and another under WFBAS) were used. Experiments were located at five districts, i.e. Gazipur, Rajshahi, Habiganj, Rangpur and Barishal (Fig. 1). The locations cover the central, northern, northwest, northeast and southern parts of the country. The climatology (1980–2020) of the winter season (November to May) is shown in Fig. 2.

Experimental design

Two-year field experiments were conducted under FP and WFBAS crop management systems at five locations in the winter seasons of 2019–2020 and 2020–2021. The two crop management systems, i.e. FP and WFBAS, were one of the treatment factors in the experiments. At each location, two farmer's fields were managed by two different farmers, each with one crop management system. A randomized complete block design with three replicates and six varieties was laid out at each farm, one under FP and one under the WFBAS crop management system. The size of each plot was 11 m long and 10 m wide with hill-to-hill distance. The plots and blocks were separated by 0.4 m and 1 m, respectively. The plots' outer rows were used as borders on both ends. Six high-yielding and stable rice varieties (BRRI dhan28, BRRI dhan29, BRRI dhan88, BRRI dhan89, BRRI dhan92 and BRRI dhan96) were used in both crop management systems at each location. The seeding and transplanting of varieties were performed based on location-specific environmental conditions (Table 1).

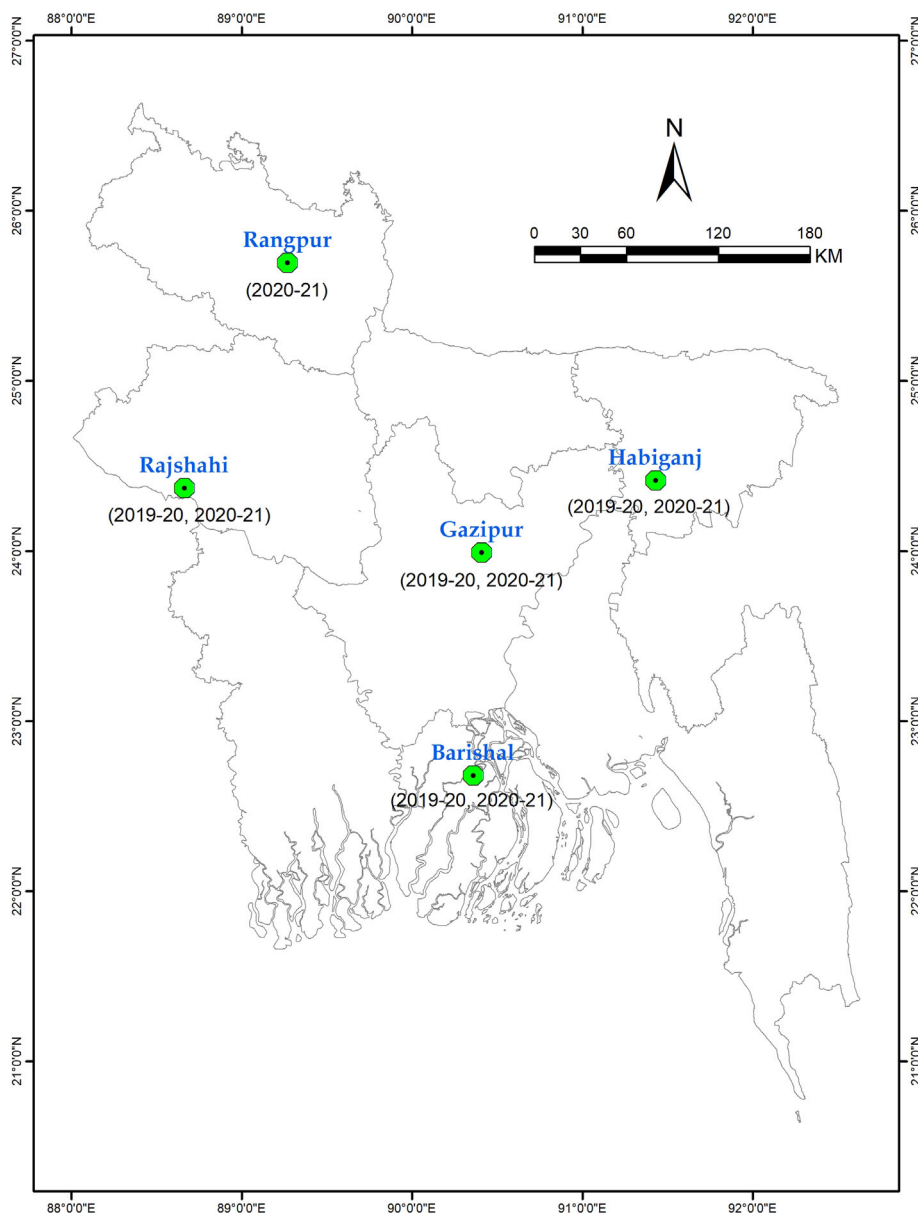


Figure 1. Location map of the study site.

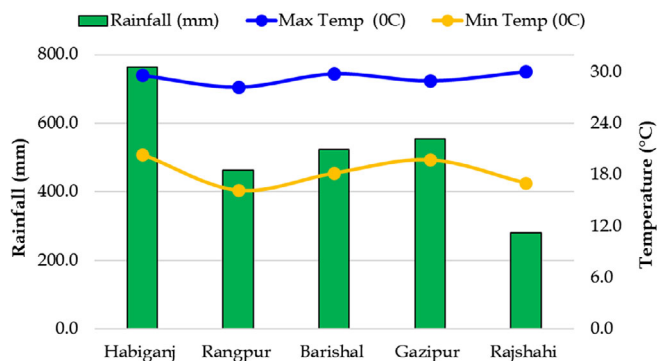


Figure 2. Climatology of different experimental locations in winter rice season.

Crop management systems

At each location, two farms were managed, one under the FP management system and one under the WFBAS management

system. As an example, two farms at the Ghazipur location in 2020–2021 under two crop management systems are shown in Fig. 3.

FP management system

In the FP management system, no specific advisory services were provided to the farmers. They managed sowing, transplanting, irrigation, weeding, fertilizer, insecticides, herbicides and fungicide use according to their usual or former management practices. The data on input use, agronomic management, yield parameters and prices were collected by BIRRI staff from these trials.

WFBAS management system

The trials under the WFBAS management system followed the advisory service generated by BIRRI. The weather research and forecasting model was employed to forecast location-specific temperatures and weather-related parameters. The Integrated

Table 1. Cultural information of field trials

Location	Date of seeding	Date of transplanting	Date of maturity
2019–2020			
Gazipur	30 Nov 2019	14 Jan 2020	20 Apr–10 May 2020
Rajshahi	27 Nov 2019	7 Jan 2020	14 Apr–6 May 2020
Habiganj	22 Nov 2019	4 Jan 2020	11 Apr–1 May 2020
Barishal	4 Jan 2020	15 Feb 2020	23 May–11 Jun 2020
2020–2021			
Gazipur	26–28 Nov 2020	13–15 Jan 2021	16 Apr–6 May 2021
Rajshahi	2 Dec 2020	17–18 Jan 2021	22 Apr–14 May 2021
Habiganj	6 Dec 2020	20 Jan 2021	26 Apr–17 May 2021
Barishal	2 Dec 2020	20 Jan 2021	20 Apr–12 May 2021
Rangpur	30 Nov 2020	12–13 Jan 2021	19 Apr–11 May 2021

Rice Advisory System (IRAS) was developed by BRRI to disseminate advisory bulletins to farmers through the local government agriculture department using a mobile network service. A screenshot of the IRAS system is shown in Fig. 4. The advisory bulletin was based on location-specific forecasts of weather and crop stage. Each bulletin contained advice for crop protection, fertilization application and crop nutrition based on the weather forecast and keeping in view the growth stage of the crop. The input used in both crop management systems was recorded by BRRI staff, and is given in the supporting information (Tables S1 and S2).

Assessments

The labor cost and cost for input use for each experiment were calculated. The details of all costs and input used for each experiment are given in Table S1 of the supporting



Figure 3. Example of an experimental site under two crop management systems at the Ghazipur location in 2020–2021. (a) FP and (b) WFBAS.

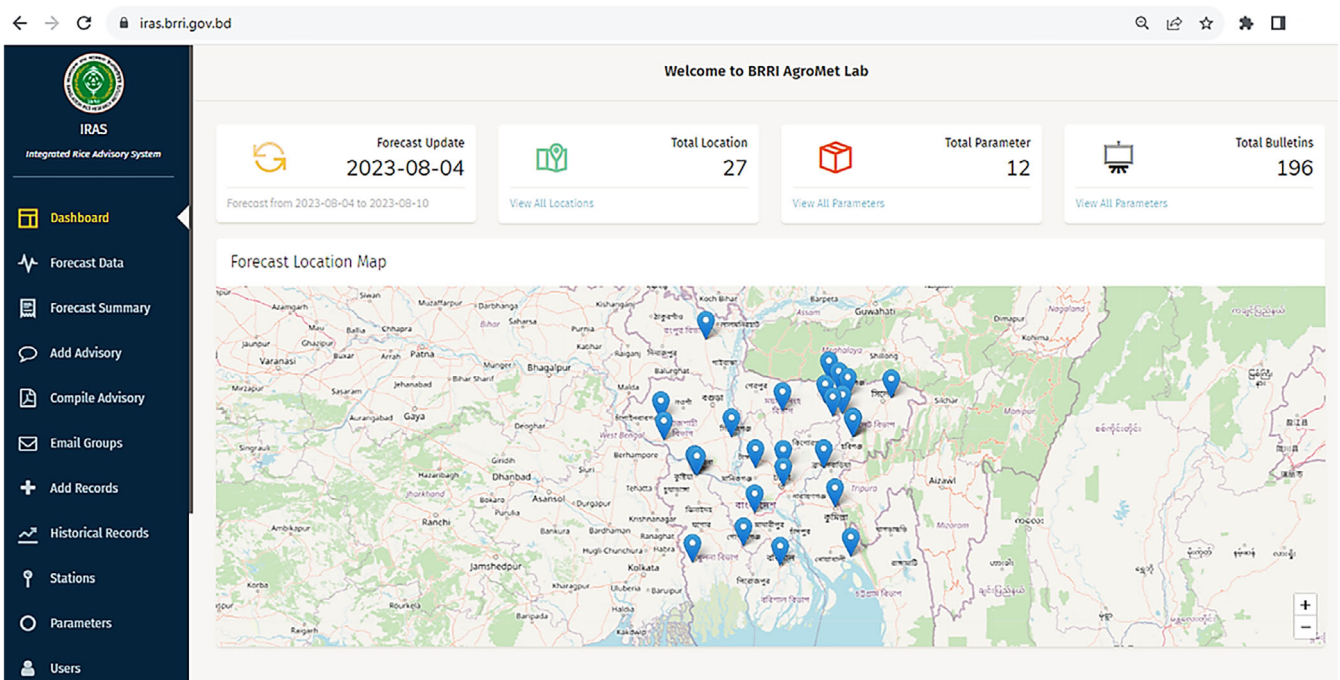


Figure 4. IRAS used for weekly weather forecast visualization, advisory generation and dissemination for different experimental locations.

information. The plots' outer rows were used as borders on both ends. A strip of 10 m × 9 m in the center of each plot was collected. Grain yield in tons per hectare was then calculated at 14% moisture content.

STATISTICAL ANALYSIS

Yield analysis

The grain yield in tons per hectare (t ha⁻¹) at 14% moisture content was computed. The following mixed model was fitted for grain yield:

$$\begin{aligned} \text{Yield}_{mlkji} = & \mu + M_k + G_i + (MG)_{ik} + Y_m + L_l + (YLMB)_{mlkj} \quad (1) \\ & + (YM)_{mk} + (YG)_{mi} + (YL)_{ml} + (LM)_{lk} \\ & + (LG)_{li} + (YMG)_{mki} + (YLM)_{mlk} + (YLG)_{mli} \\ & + (LMG)_{lki} + (YLMG)_{mlki} + e_{mlkji} \end{aligned}$$

where Yield_{mlkji} is the mean yield of the i th genotype in the j th block in the k th management at the l th location and in the m th year. Here, μ is the intercept, M_k is the fixed main effect of the k th management, G_i is the fixed main effect of the i th genotype, $(MG)_{ik}$ is the ik th fixed genotype–management interaction effect, Y_m is the random main effect of the m th year, L_l is the random main effect of the l th location and $(YLMB)_{mlkj}$ is the j th random block effect nested within management, location and year. The effects $(YM)_{mk}$, $(YG)_{mi}$, $(YL)_{ml}$, $(LM)_{lk}$ and $(LG)_{li}$ are the two-way random interaction effects of year–management, year–genotype, year–location, location–management and location–genotype, respectively. The effects $(YMG)_{mki}$, $(YLM)_{mlk}$, $(YLG)_{mli}$ and $(LMG)_{lki}$ are the three-way random interaction effects of year–management–genotype, year–location–management, year–location–genotype and location–management–genotype, respectively. The effect $(YLMG)_{mlki}$ is the four-way random interaction effect of year–location–management–genotype and e_{mlkji} is a random error. For all random terms including management and error, management-specific variances were fitted.

An important point to be made here is that the two experiments were conducted in adjacent fields at a location in a given year, one managed according to FP and one according to WFBAS management system. In this case, we need to account for a random effect of the management–trial (MT) combination at a year–location combination; however, this effect is confounded with year–management–location (YML), assuming the trial field changes from year to year. As mentioned in Piepho *et al.*,¹⁵ the sum of these two variances for these effects still can be estimated, thus providing a valid error term for treatment comparison. For the risk assessment, we need to acknowledge that the variance for the (YLM) effect will be slightly inflated due to the confounding with the field effect, so our risk assessment will be on the conservative side.

Economic analysis

A partial budget is a decision support tool widely used to assess the relative economic viability of farm businesses from two alternative production options or technologies.^{16,17} The budgeting technique was applied in the present study to evaluate the economic viability of rice farming under the FP and WFBAS crop management systems in Bangladesh.

Following Rabin *et al.*,¹⁸ partial budget analysis was applied to analyze the costs and returns of rice cultivation from the current

FP scenario and alternative WFBAS scenario as a way of determining the financial impact of replacing FP with WFBAS (Table 2).

Risk analysis

Usually, it is assumed that irrespective of the environment, the distribution of yield is normal.¹⁹ The critical normality hypothesis can be tested graphically or empirically. Under the normality assumption, we may estimate the probability of falling k th crop management system (CS) yield y_{kj} below θ in an arbitrarily selected environment j through the following equation¹⁹:

$$P(y_{kj} < \theta) = \Phi[(\theta - \mu_k) / \sigma_{kk}] \quad (2)$$

where Φ is the cumulative distribution function of the standard normal distribution. The possibility of a CS's yield dropping below a definite level depends on mean μ_k and variance σ_{kk}^2 of that CS. Plotting $P(y_{kj} < \theta)$ for various values of θ generates effective information about the CS's performance. Assuming the average system performance over the six tested varieties, the variance σ_{kk}^2 can be computed from the estimates of variance components for between-trial effects given by Model (1) as

$$\sigma_{kk}^2 = \frac{\sigma_Y^2 + \sigma_L^2 + \sigma_{YL}^2 + \sigma_{YM(k)}^2 + \sigma_{LM(k)}^2 + \sigma_{YLM(k)}^2 + (\sigma_{LG}^2 + \sigma_{YG}^2 + \sigma_{YLG}^2 + \sigma_{LMG(k)}^2 + \sigma_{YMG(k)}^2 + \sigma_{YLMG(k)}^2)}{6} \quad (3)$$

Plotting $P(y_{1j} < \theta)$ versus $P(y_{2j} < \theta)$ against different values of θ , the two CSs considered (FP and WFBAS, say) can be compared.^{20–23} It frequently turns out that one CS has less risk than the other irrespective of the critical level θ , which creates a scope for the user to specify θ as needed.

Choosing a specific critical level θ may be difficult. An alternative is to compare CSs directly in terms of risk. A CS can be observed as more desirable than others if it performs better with a probability of more than 0.5. The easiest method to estimate the probability that WFBAS outperforms FP is to examine both CSs in a larger number of different environments, calculate the difference $D_{kj} = y_{2j} - y_{1j}$ each of them and determine the frequency with which $D_j > 0$. When the normality of yields/gross margins can be expected, a substitute is to compute the probability by²⁴

$$P(D_j < 0) = \Phi[\delta / \sigma_D] \quad (4)$$

Table 2. Concept of partial budgeting

Costs	Benefits
(a) Additional costs Costs incurred as a result of using WFBAS in rice cultivation	(c) Additional returns Returns received from rice cultivation by using WFBAS
(b) Reduced returns Returns forgone as a result of not using the usual FP	(d) Reduced costs Costs that will no longer be incurred as a result of giving up the usual FP
(e) Total costs = (a + b)	(f) Total benefits = (c + d)
(g) Net return = (f – e)	(h) Benefit–cost ratio = (f/e)

where $\delta = \mu_2 - \mu_1$ and σ_D^2 is the variance of a difference D_j in a randomly chosen environment, i.e.

$$\begin{aligned} \sigma_D^2 &= \text{Var}(D_j) \\ &= \left[\sigma_{YM(2)}^2 + \sigma_{LM(2)}^2 + \sigma_{YLM(2)}^2 + \left(\sigma_{LMG(2)}^2 + \sigma_{YMG(2)}^2 + \sigma_{YLMG(2)}^2 \right) / 6 \right] + \left[\sigma_{YM(1)}^2 + \sigma_{LM(1)}^2 + \sigma_{YLM(1)}^2 + \left(\sigma_{LMG(1)}^2 + \sigma_{YMG(1)}^2 + \sigma_{YLMG(1)}^2 \right) / 6 \right] \end{aligned} \quad (5)$$

Table 3. Mean yield under two crop management systems

Treatment	Mean yield [§] (t ha ⁻¹)	Standard error
FP	6.57 ^a	0.2719
WFBAS	7.03 ^b	0.2656
WFBAS – FP	0.46	0.1139
ANOVA		
Effect	F value	Pr > F
Management	18.91	0.0127*
Variety	7.04	0.0923 ^{ns}
Management × variety	1.00	0.5279 ^{ns}

Differences in treatment effects are shown with different letters ($\alpha = 0.05$). The *p* values correspond to global *F*-tests for the difference between the levels of the indicated effects.
§ Mean yields followed by a common letter are not significantly different at the 5% level.

Table 4. Estimates of variance components of random effects

Component	Management	Estimate	Standard error
Year		0.0879	0.1905
Location		0.0198	0.0846
Year × location		0.1120	0.1027
Year × management	FP	0	0.0706
	WFBAS	0	—
Location × management	FP	0	0.0331
	WFBAS	0.0039	0.0361
Year × location × management	FP	0	0.0394
	WFBAS	0.0246	0.0443
Year × location × management × replication	FP	0.0007	0.0034
	WFBAS	0	0.0012
Location × variety		0.0103	0.0390
Year × variety		0.0004	0.0321
Location × management × variety	FP	0	0.0327
	WFBAS	0	0.0211
Year × management × variety	FP	0.0605	0.0566
	WFBAS	0	0.0352
Year × location × variety		0.0875	0.0457
Year × location × management × variety	FP	0.0137	0.0349
	WFBAS	0	—
Error ^a		0.0947	

^a Average error variance across environments.

RESULTS

Yield enhancement

The result of the linear mixed model reveals that the combined effect of management verified a significant effect on crop yield (Table 3), indicating that the yield of rice varieties significantly differed between the two crop management practices, i.e. FP and WFBAS. However, the variation of varieties did not generate a significant influence on rice yield for both management practices. Moreover, the interaction effect of variety and management was not significant. Therefore, there was strong evidence that management was a significant contributor to enhancing rice yield rather than choice of variety.

The mean yield was significantly different for FP and WFBAS, with a higher yield of about half a ton more in WFBAS than FP (Table 3). By comparison, a study conducted in the Uttara Kannada district of Karnataka indicated that actual yield increased due to the adoption of advisory services to the extent of 0.2 to 0.3 t ha⁻¹ in the rice crop.²⁵

The estimates of the variance components are presented in Table 4. Results indicate that the year, location and year-by-location interaction were the most vital factors in terms of variance components, followed by year-by-location-by-variety interaction and year-by-management-by-variety interaction. Year-by-management and location-by-management-by-variety interactions are negligible. The estimates of the variance component of location-by-variety interaction suggest substantial variability in the variety performance at different locations.

Economic analysis

It was found that farmers can earn an additional US\$229.33 per hectare from winter rice following the WFBAS instead of FP because WFBAS is less cost-intensive (e.g. low production cost) but more productive (e.g. higher yield) than FP (Table 5). The result indicates that winter rice farming following WFBAS can enhance farm income, household rice self-sufficiency and overall food security. The partial budget analysis showed that farmers who used the WFBAS crop management system can make more profit than those who used the FP management system. Therefore, replacing the usual FP with WFBAS would boost rice productivity, reduce the risk of cultivation and increase farmers' income in Bangladesh. Thus, large-scale dissemination of WFBAS could strengthen farmers' well-being. Further, weather forecasts and weather-based agrometeorological advisories also help increase the economic benefit to farmers with appropriate crop management practices.²⁶

Table 5. Partial budget for winter season rice under FP and WFBAS crop management systems (in US\$)

Item	FP	WFBAS
Costs incurred	1601.40	804.71
Returns forgone	919.37	1716.08
Net profit	682.03	911.36
Profit difference	229.33	

Farmers do not have to bear any establishment and/or operational costs for using WFBAS in rice cultivation.

Table 6. Mean rice yield and gross margins from nine environments (location × year) from FP and WFBAS crop management systems

Environment (location × year)	Yield (t ha ⁻¹)			Gross margins (US\$000)		
	FP	WFBAS	Increased yield compared to FP	FP	WFBAS	Increased gross margins compared to FP
2020						
Barishal	6.06	6.76	0.70	0.60	0.89	0.29
Gazipur	6.22	6.72	0.50	0.66	0.90	0.24
Habiganj	6.20	6.80	0.60	0.82	1.08	0.26
Rajshahi	6.33	6.85	0.52	0.88	1.16	0.28
2021						
Barishal	6.46	7.04	0.58	0.51	0.74	0.23
Gazipur	6.19	6.43	0.24	0.50	0.65	0.15
Habiganj	7.29	7.44	0.15	0.63	0.74	0.10
Rajshahi	7.28	8.05	0.77	1.07	1.37	0.30
Rangpur	6.88	7.33	0.45	0.40	0.58	0.18
Mean ^a	6.57	7.03	0.46	0.67	0.90	0.23
Variance ^a	0.24843	0.26457	0.04087	0.04125	0.07243	0.00514

^a Mean and variance are computed using Model (1) and Eqns (3) and (5).

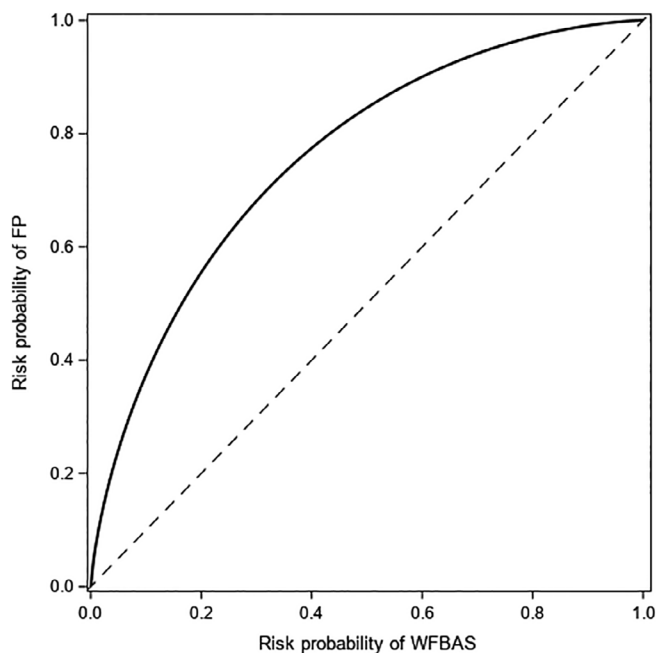


Figure 5. Risk probability of yield from two cropping systems, i.e. FP against WFBAS (solid line). The dotted line shows equal risk.

Risk analysis

The yield and gross margins for each environment (location × year) from the two crop management systems are given in Table 6. The variances for each cropping system were computed by Eqn (3) and using estimates of variance components from Model (1) which are given in Table 4.

Risk of yield from two cropping systems

Using mean and variance given in Table 6, we can compute the risk probability using Eqn (2) that yield falls below a threshold θ for a crop management system. For example, when the threshold is $\theta=6$, we can compute the probability for the FP system as

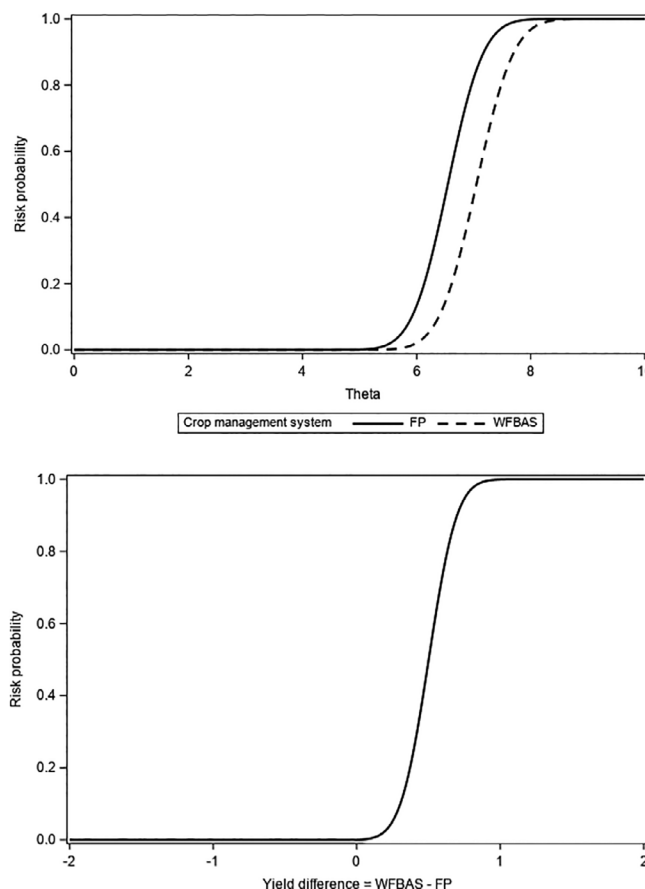


Figure 6. Risk probability of yield against threshold (θ) for two crop management systems. FP is shown by the solid line and WFBAS by the dotted line (top). Risk probability against yield difference from the two crop management systems (bottom).

$$P(y < 6) = \Phi \left[\frac{6 - 6.55}{\sqrt{0.24843}} \right] = 0.134$$

and for the WFBAS system, we can have

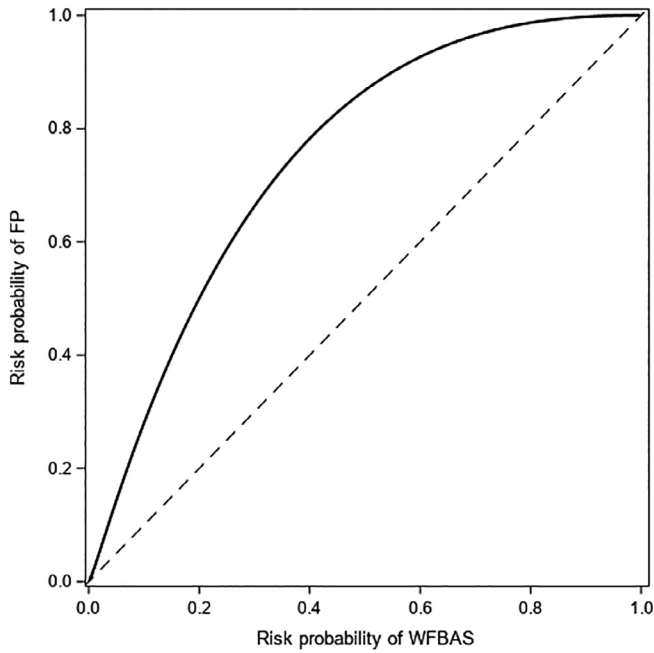


Figure 7. Risk probability of gross margins from two crop management systems, i.e. FP against WFBAS (solid line). The dotted line shows equal risk.

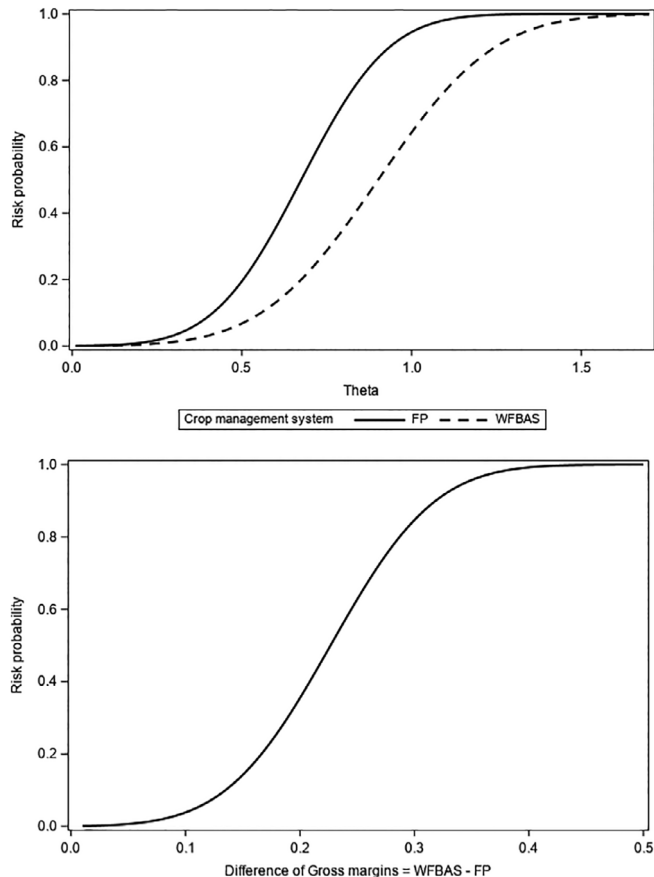


Figure 8. Risk probability of gross margins against threshold (θ) for two crop management systems. FP is shown by the solid line and WFBAS by the dotted line (top). Risk probability against the difference of gross margins from two cropping systems (bottom).

$$P(y < 6) = \Phi \left[\frac{(6 - 7.05)}{\sqrt{0.26457}} \right] = 0.021$$

We can also compute the risk probability of the yield differences between the two management systems (WFBAS – FP) for each environment using Eqn (4):

$$P(d < 0) = \Phi \left[\frac{(0 - 0.501)}{\sqrt{0.04087}} \right] = 0.0066$$

Thus, there is a 0.66% chance that $d = \text{WFBAS} - \text{FP}$ will be negative, i.e. FP will be superior to WFBAS. We can compute these probabilities for a range of values of the threshold θ and then plot one probability versus the other. Figures 5 and 6 display the risk curves of FP versus WFBAS. The plot represents that WFBAS has less risk, regardless of the level θ , as the whole plotted curve lies above the equal risk line. Note that in terms of risk, WFBAS is better than FP, despite the greater environmental variance.

Risk of gross margins for two crop management systems

The risk analysis of gross margins for the two crop management systems can be performed using Eqns (2) and (3). Figures 7 and 8 display the risk curves of FP versus WFBAS. The plot represents that WFBAS has less risk, regardless of the level θ , as the whole plotted curve lies above the equal risk line.

DISCUSSION

WFBAS is considered an important means to improve farm outcomes by aiding the decision-making of the farmers about various operations (such as irrigation, sowing, fertilizer application and plant protection) well ahead of time. The aim of this study is to evaluate the impact of WFBAS on the use of inputs in rice farming in Bangladesh. Rice cultivation under the traditional FP system usually uses more inputs than the WFBAS management system, resulting in higher production costs. For example, around 2 kg more seeds were used with FP technology. FP was found to be more labor-intensive than WFBAS. Farmers used almost 840 laborer hours per hectare on average under FP, whereas it was around 720 laborer hours under the WFBAS management system. The reason behind less labor use in WFBAS is less input use. To WFBAS is attributed the function of the application of fertilizer to the field at the right time, considering the application time and quantity prescribed by BRRI. The farmers who followed the WFBAS were able to reduce their use of fertilizer by 16% and irrigation water by 23% while maintaining or even increasing their yields compared to those who did not follow that system. In addition, the relationship between temperature and rainfall was considered when applying fertilizers. The study also found that the services helped farmers adopt more efficient irrigation scheduling practices, which contributed to the reduction in water use. Usual FP farmers, because of not considering the forecasted rainfall information, provided six more irrigations. In terms of irrigation, FP farmers applied substantially more irrigation, which may raise groundwater pressure (Fig. S1). WFBAS technology can help to make more informed decisions about when and how much to irrigate. Proper and timely irrigation enriched the crops of WFBAS farmers, contributed to an increase in yield and reduced cost of production. Das²⁷ and Gupta et al.²⁸ also found that traditional farmers use 5% more chemical fertilizers and 17% more irrigation water than farmers who followed some advisory services.

We also found in this study that farmers who followed WFBAS were able to reduce their use of herbicides by 52%, insecticides by 40% and fungicides by 26% while maintaining or even increasing their yields compared to those who did not receive the services (Fig. S2). Dupdal *et al.*²⁹ found that traditional farmers used 33% and 71% more herbicides and pesticides, respectively, compared to advisory-based management. Under WFBAS, the application of herbicides, pesticides and fungicides considers the relationship of different forecasted weather parameters such as temperature, rainfall and humidity with different stages of growth of rice. WFBAS management incorporated pest and disease information, recommending whether and when it is appropriate to apply pest or disease controls. Wind forecasts also play a part in this decision, as fungicidal or insecticidal chemicals for spraying must be applied when wind situations are not likely to cause sprayed substances to miss their aims (Fig. S2). A total of 500 g of herbicide was used inappropriately, which is more than double the amount applied in WFBAS. In addition, more insecticides and fungicides were used in FP than in WFBAS. The excessive use of inputs increased the labor requirement in FP compared with WFBAS. Finally, excess use of all inputs results in improper use of resources, and it has an adverse side effect on the environment. Considering weather and climate variability in utilizing the aforementioned inputs ensures adequate and proper use. The experimental findings of this study reveal that farmers practicing traditional rice field management applied more fertilizers, herbicides, insecticides and fungicides than farmers following the WFBAS technology, which is harmful to the environment.

Applications of fertilizers, herbicides, insecticides and fungicides all have a relationship with time, temperature and rainfall, which FP does not consider, but WFBAS technology considers these factors.

The optimal and timely use of inputs in the WFBAS system can lower production costs by an average of 13% (Fig. 9). Several studies like those of Gupta *et al.*,²⁸ Chakraborty *et al.*³⁰ and Chattopadhyay and Chandras³¹ also reveal that advisory services can reduce agricultural production costs by 5–12% as compared to traditional farming. The results of the benefit–cost ratio in this study showed that the WFBAS management system is an economically viable choice for farmers. Notably, the benefit–cost ratio of WFBAS technology is higher (2.17) than that of FP technology (1.75) due to the use of fewer inputs in relation to the weather forecast (Fig. 9).

This study discovered that by implementing WFBAS technology, rice yield increased by 7%. Nevertheless, the effective utilization of weather information can significantly decrease overall crop losses.^{26,32} Das²⁷ also showed a net improvement of 6.7–15% in overall rice yield when an advisory service was used as compared to the traditional approach in farmers' fields. Profit to farmers due to the adoption of agrometeorological advisory services was enhanced due to the adoption of weather-based crop management practices which include timely land preparation and sowing, adoption of recommended seed rate and suitable varieties, timely weeding, maintaining soil moisture, pesticide application, irrigation and harvesting, which helped in realizing higher yield of cropping systems.

Furthermore, the WFBAS technology was about 31% more profitable than FP technology (Fig. 9). The optimal and timely use of

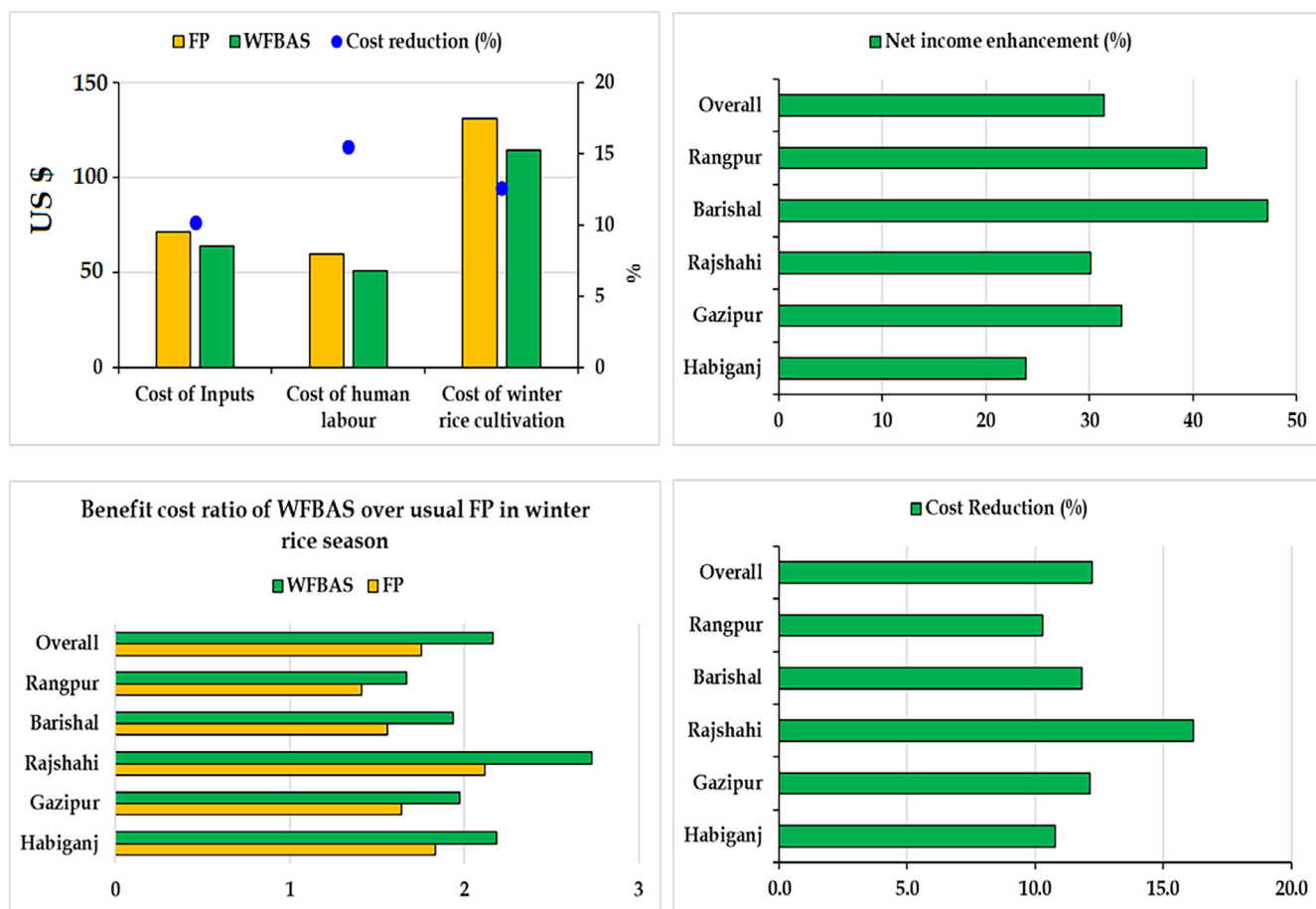


Figure 9. Economic performance of WFBAS over usual FP in winter rice season.

irrigation, fertilizers and pesticides are the major reasons for the decrease in production and labor costs that ultimately increase the overall profit of WFBAS farmers as compared to traditional farmers. Due to the assessment of weather risk in advance for rice cultivation, WFBAS farmers required fewer inputs overall. As a result, the WFBAS crop management system can make proper use of resources in rice cultivation. Simultaneously, the proper use of agricultural inputs reduces environmental pollution.

CONCLUSION

The results of the implementation of WFBAS were highly useful as, besides the weather forecast information, it also provides technical assistance on cultivation issues such as transplanting and fertilizer application in time, timely irrigation and pesticide application. It also saves resources like water, labor, electricity and fuel by precisely scheduling irrigation. Besides, implementing WFBAS has the potential to enhance yield, lower production costs, reduce input requirements by properly using resources, obtain higher profit, ensure better agronomic practices such as managing fertilizers for rice in terms of proper amount and time, fewer labor requirements, lower pest and disease infestation risks and a better capacity to handle stresses, particularly drought, flood and extreme events. WFBAS technology reduces the risk of rice cultivation in terms of yield and return. However, the successful implementation and wider adoption of WFBAS require technical knowledge and assistance at the field level and require strong collaboration among researchers, meteorologists, extension officials and farmers. This technology has the potential to significantly improve farmer welfare and food security in Bangladesh. As a result, the adoption of WFBAS will significantly enhance the national return from agriculture by increasing rice productivity and minimizing risks.

AUTHOR CONTRIBUTIONS

Waqas Ahmed Malik and Niaz Md. Farhat Rahman performed statistical analyses, prepared the figures and wrote the full manuscript. Md. Shahjahan Kabir supervised the trials. Md. Chhiddikur Rahman, Rokib Ahmed, ABM Zahid Hossain, Md. Mofazzel Hossain, Tuhin Halder, Md. Khairul Alam Bhuiyan and Mohammad Ashik Iqbal Khan conducted trials and recorded observations at multiple locations. Raihanul Haque Khan and Nazmul Ahasan implemented agrometeorological models in the WFBAS advisory application. Hans-Peter Piepho provided suggestions regarding the statistical models and analysis. Hans-Peter Piepho and Md. Azizul Baten helped in the editing of the manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflict of interest.

ETHICS STATEMENT

The authors declare that the experiments comply with the current laws of the countries in which the experiments were performed.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

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