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STRATEGIC ANALYSIS FOR SUSTAINING PRODUCTION AND SAVING WATER THROUGH INCREASING *T. AUS* AND *T. AMAN* RICE CULTIVATION IN BANGLADESH

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Abstract

Rice is a water-loving crop. Among the three rice growing seasons of Bangladesh, water demand is met in *Boro* through intensive irrigation largely utilizing underground water. Increasing pressure on underground water can cause water crisis in future hindering irrigation coverage of the entire production area in the season. With this background, this study explored revised seasonal land allocation between the rice growing seasons aiming probable land release from *Boro* season to sooth water crises. Options were also included in utilizing fallow land in their process. A conceptual framework was developed to address the issue. For the analysis, published and unpublished data were used. A model was developed and applied to simulate rice area, yield and production under four different scenarios. The results shows that the area under *T. Aus* can be increased from 1.28 to 2.0 mha in 2030 by utilizing 15% fallow land and shifting 5% of *Boro* area to *T. Aus*. Utilization of better varieties and proper management practices would ensure the target of rice production equilibrium in the proposed change scenarios, whereas mitigate potential water crisis by 4725 million liters. To establish these potentials, the study highlighted a number of pre-requisites to be looked into by various stakeholders.

Keywords: *T. Aman*, *T. Aus*, Cropping pattern, Intensive irrigation, Simulation.

Introduction

Rice is the staple food for Bangladeshi people and will continue to remain so in the future. In the year 2019, the net cultivated area was about 8.83 million hectares (mha), among them 7.88 mha land was irrigated (BBS, 2023). Bangladesh is the 3rd largest country in the world with respect to rice production (FAO, 2022). Because, rice is grown in all the three crop growing seasons of a year and it occupies about 11.68 mha land where production is 40.697 million metric tons (mmt) of the year 2023-24 (BBS, 2024). All modern *Boro* varieties are cultivated as irrigated rice, whereas only a small proportion of the *T. Aus* and *T. Aman* crops (7% and 5%, respectively) receive either full

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or supplemental irrigation. Production of 1 kg of irrigated rice mainly *Boro* type requires about 1606 liters of water as estimated in the north western region (Amin & Tuhin, 2025). With respect to natural water availability, about 96% of the total rainfall occurs during the period of April to October, statistically 13% of total rainfall occurs during post-monsoon (October and November) and only 7% of total rainfall occurs during dry season (December to February) (DoE, 2024). Drought conditions prevail over most areas of Bangladesh during the period of November to April. A rice crop cannot sustain during this period with rainfall alone. Due to very limited availability of rain water during dry season (November-April) the *Boro* rice is fully dependent on irrigation.

Area irrigated by groundwater has jumped to 80% from 16% (BADC, 2013). About 79% of the total cultivated area in Bangladesh is irrigated by groundwater, whereas the remaining is irrigated by surface water (Contaminants, 2023). So, groundwater is the major source of rice irrigation, as surface water is scarce during dry season. Groundwater is extensively used as a reliable and dependable source of irrigation. Large number of Deep Tube Wells (DTWs), Shallow Tube Wells (STWs) and Hand Tube Wells (HTWs) have been installed for this purpose in the country. Due to excessive and unplanned water uplifting, groundwater level constantly declines which is heading to imbalance of local biodiversity in near future. Ali *et al.* (2012) mentioned that, water-table depths could shrink by double by 2030 in the Barind area if current trend of withdrawal continue. Karim, N. N. *et al.* (2025) figured out the supply of and demand for thirty-five crops using ARIMA model for the period of 2025-2050 with base year of 2021, which escaped a focus on water crises or saving water in future.

Targeting high yield by providing irrigation facility with a higher cropping intensity is the most logical way of raising the total rice production at the national level. So, side by side the rational way should be to bring more fallow land under cultivation in *T. Aus* season with growing modern varieties because we still have almost 0.431 mha of land are being fallowed. We need to utilize it. So, rice area can be increased in *T. Aus and T. Aman* season adopting techniques of using rain water or partial irrigation which will allow groundwater saving to a large extent. This study was carried out to support policy guidelines for increasing *T. Aus* rice production and thereby reducing pressure on irrigation using groundwater in *Boro* season. This will contribute to strategy development for sustaining the rice production to match the demand with the limited land and water resources of Bangladesh.

Approaches and Methods

Conceptual framework

Sustaining rice production by using underground irrigation water from underground is a major driver of irrigated rice cultivation where irrational uplifting poses a great challenge of water security in future. Saving water is an option to mitigate the future challenges of water crises. There are a number of alternative options sketched in the Fig.1.

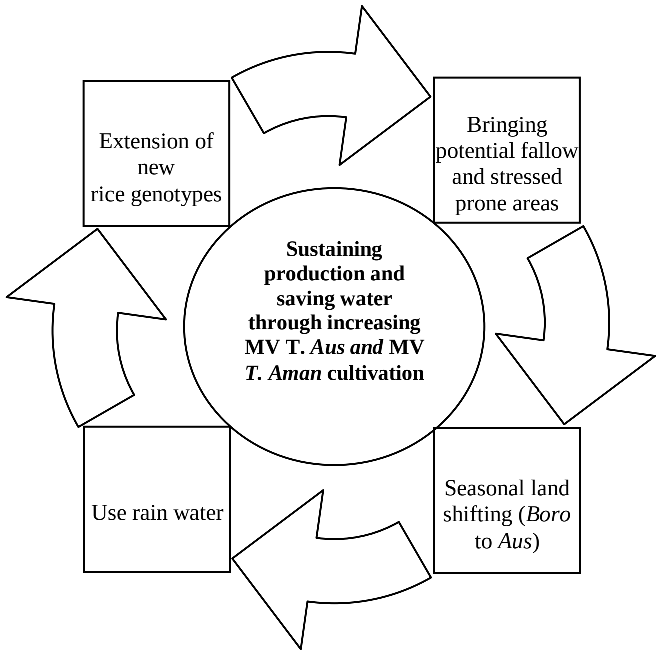

Fig. 1. Conceptual framework of the study

Continuous effort for development of stress tolerant varieties and improved rice genotype has been made but many of the technologies are still not in practice or underutilized. Necessary investment and for extension of those varieties in *T. Aus* and *T. Aman* season would enormously contribute to national rice security. Many stress prone areas remains fallow due to lack of proper attention and policy execution and those will be the options of increasing *T. Aus* and *T. Aman* cultivation and reduce *Boro* cultivation area. Therefore, rice area should be increased in *T. Aus* season by adopting techniques of using rain water or partial irrigation which will allow groundwater saving to a large extent. On the other hand, natural calamity is the potential risk.

Terminology

Terminologies used in this study includes Rabi season for dry season-irrigated or Boro cultivation, Kharif-I or upland rice for *T. Aus* and wetland rice or Kharif-II for *T. Aman*. Modern variety is abbreviated as MV and local variety as LV. Million hectare is abbreviated as mha, tons per hectare as t/ha and million metric tons as mmt. Planted area and harvested area represents the area devoted to rice cultivation during transplanting and harvesting, respectively.

Data collection

This study used secondary data gathered from published and unpublished sources, notably Bangladesh Bureau Statistics (BBS), Bangladesh Agricultural Census (BAC) and Bangladesh Rice Research Institute (BRRI). Farm and retail prices were collected from World Rice Statistics (WRS). Exports, imports, and stock change of rice were gathered from the Food and Agriculture Organization (FAO) as well as GDP and GDP deflator are from World Data Bank (World Bank). Climatic data of temperature, rainfall, and solar radiation were collected from the Data Distribution Centre of the IPCC. Forecast climatic variables from 2010 to 2030 was used from Model for Interdisciplinary Research on Climate (MIROC5), General Circulation Model (GCM) of the University of Tokyo, NIES (National Institute for Environmental Studies) and JAMSTEC (Japan Agency for Marine-Earth Science and Technology).

Analytical models

In order to carry out simulation under the strategies of *T. Aus* rice increasing and adaptation of climate change, a rice supply and demand model was developed to understand the future situation of rice under climate change in Bangladesh. Supply and demand model for rice in Bangladesh consists of sixteen structural equations and nine identities, including temperature, rainfall and solar radiation as climatic variables. The basic structure of the simulation model for supply and demand structure for market equilibrium condition was adopted from Furuya and Meyer (2008), Furuya *et al.* (2010), and Salam *et al.* (2017).

The market equilibrium condition was defined as

$$SS_{Rt} = DD_{Rt} \ldots\ldots (1)$$

Where, SS_{Rt} stands for supply and DD_{Rt} is demand for rice

$$times\ t = 1, 2, 3, \ldots \ldots \ldots \ldots \ldots n$$

Breakdown of Market Supply of Rice (SS_{Rt})

$$SS_R = 0.67 * \sum(YR_{ivt} * AR_{ivt}) + Import_t - (Seed_t + Feed_t + Exp_t + STC_t + Wastage_t + UO_t) \ldots\ldots (2)$$

Where:

YR_{ivt} = Yield per unit area in year t

AR_{ivt} = Harvested area in year t

$Import_t$= Quantity of rice imported in year t

$Seed_t$= Quantity of rice used as seed in year t

$Wastage_t$= post-harvest and storage losses in year t

$Feed_t$ = Feeds for livestock in year t

Exp_t= Export of rice in year t

STC_t = Stock changes in year t

OU_t = Other usage

i = different seasons

and v = types of varieties

0.67 is conversion rate of rice from paddy

Given that the climate is one of the influential factors, the yield function was built up by taking time trends and climatic factors (rainfall, temperature, and sun radiation) as explanatory variable along with technology advancements (modern genotypes, various machinery, and nutrients). To predict how farmers will react to market prices and previous season climate, the area function was developed using the combined assumptions of partial adjustment and adaptive expectations (Nerlove, 1958). Therefore, product of rice yields and areas by variety and season finally generated national rice production in the simulated model (Salam *et al.* 2017).

$$QR_t = \sum(YR_{ivt} * AR_{ivt}) \ldots\ldots..(3)$$

Where, QR_t= total rice production from different season.

In this study, harvested area of three different seasons was applied in the model. Grain yield and production of different rice varieties (modern and local) in different seasons (*T. Aus, T. Aman* and *Boro*) was taken for analyzing with this model.

The 'harvested' area (used instead of 'planted' area in this model) functions were specified based on the Nerlovian adaptive expectation (Nerlove, 1958) model where the exogenous variable was rainfall as proxy for irrigation.

If the area function responded to the expected price and the yield did not respond to the expected price, the explanatory variables of the area function was harvested area, price, and exogenous variable in the previous year.

Development of Area function

$$AR_{ivt} = \alpha_{ivAR} + \beta_{ivAR1} * AR_{iv(t-1)} + \beta_{ivAR2} * Price_{t-1} + \beta_{ivAR3} * Rain_{t-1} \ldots..(4)$$

Where AR_{ivt} is the harvested area and $AR_{iv(t-1)}$ is the lagged area. $Price_{t-1}$ is the lagged farm price and $Rain_{t-1}$ is the lagged of seasonal rainfall in months (m) as proxy for irrigation. α_{ivAR}, β_{ivAR1}, β_{ivAR2} and $\beta_{ivAR3}$are estimated parameters, respectively which need to be estimated.

At the same time, the yield function is independent from the expectation model because the yield does not respond to the price.

Development of Yield function

$$YR_{ivt} = \alpha_{ivYR} + \beta_{ivYR1} * Trend_{iv} + \beta_{ivYR2} * Temp_{ivt} + \beta_{ivYR3} * Rain_{ivt} + \beta_{ivYR4} * srad_{ivt} \ldots(5)$$

Where YR_{ivt} is specific rice varieties yield; $Trend_{iv}$ is trend used as proxy for technological advancement. Climate variable such as $Temp_{ivt}$, $Rain_{ivt}$ and $srad_{ivt}$ are seasonal temperature, rainfall and solar radiation respectively in months. α_{ivYR}, β_{ivYR1}, β_{ivYR2}, β_{ivYR3} and β_{ivYR4} are estimated parameters, respectively which needs to be estimated. In Bangladesh, *T. Aus* (upland rainfed) season begins from the beginning of March and it is harvested in mid-August. *T. Aman* (wet season) starts from July and ends at late December and *Boro* (dry season-irrigated) begins from the mid-November of previous year and harvested in late April. In every season farmer used to grow modern variety and local varieties in their plots. The modern varieties are those, which plant height is dwarf (short/strong), leaf erect (straight), nutrient up taking capacity is high and finally those are higher yielder. On the other hand, local variety's plant heights are long and weak, leaf is flat and nutrient uptake efficiency is comparatively lower. So, those varieties provide lower yield.

Estimated area function:

$$AR_{ivt} = \hat{\alpha}_{ivAR} + \hat{\beta}_{ivAR1} * AR_{iv(t-1)} + \hat{\beta}_{ivAR2} * Price_{t-1} + \hat{\beta}_{ivAR5} * Rain_{t-1} \ldots\ldots (6)$$

Now, assume a percentage growth in area (r):

$$rAR_{ivt} = \hat{\alpha}_{ivAR} + \hat{\beta}'_{ivAR1} * AR_{iv(t-1)} + \hat{\beta}_{ivAR2} * Price_{t-1} + \hat{\beta}_{ivAR5} * Rain_{t-1} \ldots\ldots (7)$$

Where, r = percentage increase of *T. Aus* area of rice in year t

To get new parameter by subtracting eq (6) - eq (7):

$$AR_{ivt} - rAR_{ivt} = \hat{\beta}_{ivAR1} * AR_{iv(t-1)} - \hat{\beta}'_{ivAR1} * AR_{iv(t-1)}$$

$$\text{Or } (1-r) * AR_{ivt} = (\hat{\beta}_{ivAR1} - \hat{\beta}'_{ivAR1}) * AR_{iv(t-1)}$$

$$(1-r) * AR_{ivt} = (\hat{\beta}_{ivAR1} - \hat{\beta}'_{ivAR1}) * AR_{iv(t-1)}$$

When i = *Aus* season, the new parameter for 15% fallow land shifting to MV *T. Aus* cultivation as below

$$\hat{\beta}'_{ivAR1} = \frac{(r-1)*AR_{ivt}}{AR_{iv(t-1)}} + \hat{\beta}_{ivAR1} \ldots\ldots\ldots\ldots (8)$$

When i = *Boro* season, the new parameter for 5% of *Boro* shifting to MV *T. Aus* of area is as below:

$$\hat{\beta}'_{ivAR1} = \hat{\beta}_{ivAR1} - \frac{(1-r) * AR_{ivt}}{AR_{iv(t-1)}} \ldots\ldots\ldots (9)$$

The base parameter of lagged area $\hat{\beta}_{ivAR1}$ was replaced in eq (6) by the calculated changed parameter $\hat{\beta}'_{ivAR1}$in *T. Aus* and *Boro* area function, respectively, for re-simulation of the supply and demand model. The iteration of the simulation of eq (1) continued until supply and demand arrived at equilibrium condition. Finally, the re-simulation resulted in the re-adjusted areas allocation for *T. Aus, T. Aman* and *Boro*.

Determination of Scenarios

In determining the following scenarios, seasonal fallow land and shifting *Boro* areas to MV *T. Aus* were considered by using heuristic simulation of the supply and demand model. Expert opinion was also validated through repeated calibration. The scenarios were as follows:

a) Scenario 1: Business-As-Usual
b) Scenario 2: 5% of *Boro* land shifting to MV *T. Aus* cultivation
c) Scenario 3: 15% fallow land shifting to MV *T. Aus* cultivation
d) Scenario 4: Combined 15% fallow and 5% of *Boro* land shifting to MV *T. Aus* cultivation

Parameters of Area equation

New parameters were estimated following scenarios using eq 8 and eq 9 which is shown in table 1.

Table 1. Estimation of parameters of area equation using scenarios

Season	Parameters		
	Base value of lagged area	5% of *Boro* area shifting	15% fallow land utilization
MV *T. Aus*	0.69	Same	0.85
MV *T. Aman*	0.71	Same	Same
MV *Boro*	0.73	0.68	Same
LV *T. Aus*	0.27	Same	Same
LV *T. Aman*	0.57	Same	Same
LV *Boro*	0.66	Same	Same

Salam et al. (2017) and author's estimation

The base value of lagged area variable of MV *T. Aus* area function was 0.69 which yielded to 0.85 after imposing 15% increase of area in the MV *T. Aus* area function. Similarly, 5% area shifting from *Boro* to *T. Aus* yielded to 0.68 from 0.73 of the lagged area variables of MV *Boro* area function.

Result and Discussion

Present status of *T. Aus*, *T. Aman* and *Boro* rice

Table 2 presents the overall rice cultivation area and production status in Bangladesh. In 2023, a total of 11.63 mha of land were utilized for rice cultivation. Among this, 9.12% of the area was allocated to *T. Aus* rice, 49.19% to *T. Aman* rice, and 41.70% to *Boro* rice. This indicates that the Rabi season (mainly *Boro*) and Kharif -2 season (mainly *T. Aman*) are the dominant periods for rice cultivation in Bangladesh. Although the cultivated area for *Boro* rice is smaller compared to *T. Aman* rice, its yield is significantly higher. However, *Boro* cultivation requires a much larger amount of irrigation water, making it resource-intensive compared to the other rice season. Therefore, it would be a wise decision to increase the cultivation of *T. Aman* and *T. Aus* rice relative to *Boro* rice, without compromising total production. By allocating comparatively less land to *Boro* and expanding the area under *T. Aman* and *T. Aus*, we can reduce the heavy dependence on irrigation during the *Boro* season. This approach would help ensure more efficient utilization of groundwater resources while maintaining overall rice production.

Table 2. Present status of *T. Aus*, *T. Aman* and *Boro* rice in Bangladesh with respect to variety type, production and yield

Crops	Varieties	Area (mha)	Yield (t/ha)	Production (mmt)	% of total production	% of total area
T. Aus	Local	0.09	1.44	0.12	0.31	0.7
	MV	0.98	2.84	2.78	7.11	8.4
Total *T. Aus*		1.06	2.73	2.90	7.42	9.1
T. Aman	Broadcast	0.22	1.09	0.24	0.62	1.9
	local	0.69	1.65	1.13	2.89	5.9
	MV	4.82	2.91	14.06	35.95	41.4
Total *T. Aman*		5.73	2.69	15.43	39.46	49.2
Boro	Local	0.02	1.90	0.05	0.12	0.2
	HYV	3.62	4.14	14.99	38.33	31.1
	Hybrid	1.21	4.74	5.74	14.67	10.4
Total *Boro*		4.85	4.28	20.77	53.12	41.7
Total Rice		11.64	3.23	39.10	100.00	100.00

Source: FY-2022-23 (BBS, 2024)

Division wise crop cultivation and seasonal fallow land

There are eight administrative division in Bangladesh and each has its unique characteristics. Because of this, their soil quality and climate conditions also vary from one another. There are number of rivers with a plenty of surface water in the Barisal region. The majority of rivers have fresh water that can be used for irrigation. MV rice cultivation is unsuitable during the Kharif-2 (*T. Aman*) season due to tidal flooding and deeper water. As a result, local variety of *T. Aman* is very popular. But in high land and medium high land MV rice can be grown where tidal water depth is within the permissible limit (40-70 cm) (Islam *et al.* 2013). Generally, irrigation is not necessary during Kharif-2 season. During dry season, about 65% land is kept fallow due to lack of irrigation facility and Rahman *et al.* (2019) also depicts that almost 29% farmers leaving most land fallow in the dry season. Some farmers cultivate *T. Aus* rice using tidal water and rain water. If irrigation facility can be developed by re-excavating the existing canals and supplying irrigation pumps on rental basis, *T. Aus* area can be increased easily. Farmers can also purchase the irrigation pumps if micro credit facility is ensured. In Rajshahi division, groundwater is mainly used during *Boro* season, if unplanned withdrawal of groundwater continues; it leads to serious environmental degradation. Recent days in some areas, shallow tubewell does not get water during the peak requirement of *Boro* rice. In considering the situation, a particular portion of *Boro* area shifting to *T. Aus* area reduces extreme pressure on ground water. As the yield of *T. Aus* rice is less, so the area fixation should be such that there is no change in total annual production. In Khulna division like as Satkhira, Khulna and Jessore areas there are water logging problem. Therefore, these areas remain fallow during the whole year. Severely affected upazilas of water logging are Keshobpur (Jashore), Tala, Satkhira Sadar and Kolaroa (Satkhira). So, it is necessary to study the root causes of water logging problem and identify solutions like rehabilitation of the coastal embankment, excavation and dredging of coastal rivers, construction of water control structure during high tide and low tide and development rice varieties for stagnant water and shallow flooded condition (up to 1.0-meter depth). In Sylhet region vast fields remain fallow during dry season. The main reasons for these fallow lands are absentee land owner and lack of irrigation facilities. There is huge amount of irrigable water in Haors. So, attempts should be made to bring those areas under rice cultivation. From table 3, 4 and 5, it can be viewed that, overall Dhaka and Chattogram division has higher percentage of fallow land which is about 9 and 8% respectively. Though, In Barishal, Chattogram, Khulna and Rangpur region has used more land in *Aman* season compare to *Boro* season because of natural calamities but in Rajshahi, Mymensingh, Sylhet and Dhaka utilized more land for *Boro* cultivation. Because of this, in that particular division we saw water scarcity for *Boro* cultivation. So, we had an opportunity to shift/reduce *Boro* land or used fallow land in *T. Aman* and *T. Aus* season which would be a potential solution to overcome water problem.

Table 3. Division wise land utilization status in Bangladesh (area in mha)

Division	Total	Not available for cultivation	Cultivable waste	Current fallow	Singe cropped	Double cropped	Triple cropped	% of Fallow land used for cultivation
Chattogram	3.39	0.62	0.08	0.07	0.27	0.60	0.20	8.00
Sylhet	1.26	0.38	0.06	0.02	0.36	0.27	0.10	2.00
Dhaka	2.05	0.59	0.07	0.13	0.38	0.58	0.23	9.00
Mymensingh	1.07	0.27	0.02	0.03	0.14	0.43	0.15	5.00
Barishal	1.32	0.25	0.01	0.08	0.38	0.25	0.11	3.00
Khulna	2.23	0.45	0.03	0.10	0.26	0.45	0.33	4.00
Rajshahi	1.82	0.45	0.01	0.05	0.17	0.74	0.38	1.00
Rangpur	1.62	0.37	0.01	0.01	0.08	0.79	0.34	3.00
Bangladesh	14.76	3.38	0.29	0.48	2.04	4.11	1.86	4.00

Source: FY-2022-23 (BBS, 2024)

Table 4. Division wise rice cultivation status in Bangladesh

Rice	Items	Barishal	Chattogram	Dhaka	Khulna	Mymensingh	Rajshahi	Rangpur	Sylhet	Bangladesh
T. Aus	Area (mha)	0.19	0.22	0.05	0.16	0.03	0.19	0.09	0.03	1.06
	Yield (t/ha)	2.40	2.66	2.52	2.85	2.68	2.97	2.87	2.92	2.73
	Production (mmt)	0.45	0.59	0.14	0.46	0.07	0.58	0.25	0.08	2.90
T. Aman	Area (mha)	0.67	0.84	0.53	0.74	0.59	0.83	1.11	0.41	5.72
	Yield (t/ha)	2.24	2.66	2.38	2.91	2.65	2.87	2.86	2.80	2.70
	Production (mmt)	1.50	2.23	1.26	2.15	1.57	2.40	3.16	1.16	15.43
Boro	Area (mha)	0.14	0.60	0.75	0.62	0.66	0.82	0.77	0.49	4.85
	Yield (t/ha)	3.98	4.05	4.45	4.37	4.22	4.35	4.29	4.22	4.28
	Production (mmt)	0.57	2.42	3.36	2.73	2.79	3.57	3.29	2.05	20.77

Source: FY-2022-23 (BBS, 2024)

Table 5. Division wise percentage use of rice is in different season of Bangladesh

Division	Area (million hectare)							
	Net cropped	Gross cropped	*T. Aus*	% *T. Aus* area of net cropped	*T. Aman*	% *T. Aman* area of net cropped	*Boro*	% *Boro* area of net cropped
Barishal	0.74	1.22	0.19	25.00	0.67	91.00	0.14	19.00
Chattogram	1.07	2.08	0.22	21.00	0.84	78.00	0.60	56.00
Dhaka	1.19	2.24	0.05	5.00	0.53	45.00	0.75	63.00
Khulna	1.05	2.18	0.16	15.00	0.74	70.00	0.62	59.00
Mymensingh	0.72	1.46	0.03	4.00	0.59	82.00	0.66	92.00
Rajshahi	1.30	2.82	0.19	15.00	0.83	64.00	0.82	63.00
Rangpur	1.22	2.71	0.09	7.00	1.11	91.00	0.77	63.00
Sylhet	0.73	1.18	0.03	4.00	0.41	57.00	0.49	67.00
Bangladesh	8.02	15.90	1.06	13.00	5. 72	71.00	4.85	60.00

Source: FY-2022-23 (BBS, 2024)

Simulation result of area, yield and production: Scenario 1

The simulation reveals that area under MV *Aus* is shrinking meaning that MV *Aus* variety is vulnerable to climate change. Furthermore, area under local *Aus* variety shows moderately constant trend under business-as-usual. In addition, area and yield of all varieties during both *Boro* and *T. Aus* season demonstrate stable performance. From table 6, it would be evident that overall output is rising. It also displayed that total production of clean rice is 39.71 mmt in the year 2030.

Table 6. Simulated area, production and yield of three rice types in Bangladesh under Business-As-Usual scenario

Items	Season	Clean rice Yield (t/ha)					Area (mha)				
		2009	2015	2020	2025	2030	2009	2015	2020	2025	2030
MV rice varieties	*T. Aus*	2.03	2.33	2.62	2.47	2.93	0.67	0.61	0.62	0.61	0.70
	T. Aman	2.49	3.04	3.08	2.67	3.29	3.85	3.89	3.83	3.95	4.12
	Boro	3.95	4.19	3.75	4.73	4.03	4.57	4.36	4.81	4.92	4.77
LV rice varieties	*T. Aus*	1.23	1.14	1.50	1.51	1.47	0.40	0.34	0.39	0.36	0.42
	T. Aman	1.48	1.78	1.76	1.67	1.88	2.31	2.29	2.12	2.03	2.03
	Boro	2.00	2.12	2.15	2.29	2.30	0.11	0.24	0.09	0.21	0.25
Total production of cleaned rice (mmt)	*T. Aus*	1.86	1.80	2.21	2.04	2.67					
	T. Aman	13.01	15.86	15.53	13.94	17.39					
	Boro	18.26	18.78	18.22	23.75	19.75					
	Total	33.13	36.44	35.96	39.73	39.81					

Source: Author's estimation from simulation.

Simulation result of area, yield and production: scenario 2

In the simulation, proxy for technologies is time trend representing technological advancement across the time. All MVs for all three seasons performs consistently meaning that the improved technologies are climate resilient. At 5% MV *Boro* area shifting condition, local varieties also demonstrate the stability capacity side by side. The area under MV *Aus* gradually increase from 0.67 mha in 2009 to 1.27 mha in 2030 under this shifting condition. Total production shows modest decrease from business-as-usual (39.81 mmt in 2030) to 5% MV *Boro* area shifting (38.71 mmt in 2030). Table7 shows that after 5% *Boro* area shifting lead to a slight drop in rice production since yield of MV *Aus* is lower than that of MV *Boro* rice.

Table 7. Simulated area, production and yield of three rice types in Bangladesh under 5% *Boro* area shifting from Simulation

Items	Season	Clean rice Yield (t/ha)					Area (mha)				
		2009	2015	2020	2025	2030	2009	2015	2020	2025	2030
MV rice varieties	*T. Aus*	2.03	2.33	2.62	2.47	2.93	0.67	1.19	1.19	1.19	1.27
	T. Aman	2.49	3.04	3.08	2.67	3.29	3.85	3.91	3.85	3.98	4.15
	Boro	3.95	4.19	3.75	4.73	4.03	4.57	3.74	4.12	4.20	4.04
LV rice varieties	*T. Aus*	1.23	1.14	1.50	1.51	1.47	0.40	0.34	0.39	0.36	0.43
	T. Aman	1.48	1.78	1.76	1.67	1.88	2.31	2.31	2.14	2.06	2.06
	Boro	2.00	2.12	2.15	2.29	2.30	0.11	0.24	0.09	0.21	0.25
Total production of cleaned rice (mmt)	*T. Aus*	1.86	3.15	3.71	3.47	4.32					
	T. Aman	13.01	15.98	15.62	14.08	17.54					
	Boro	18.26	16.17	15.61	20.34	16.85					
	Total	33.13	35.30	34.94	37.89	38.71					

Source: Author's estimation from simulation.

Simulation result of area, yield and production: scenario 3

By converting 15% of cultivable land that remained fallow under MV *Aus* rice cultivation, the area under MV *Aus* increase to 1.28 mha in 2030 and subsequently raises total rice production from 39.81 mmt at business-as-usual to 41.34 mmt at shifting 15% fallow land to MV *Aus* in 2030. The significant advancement results from the increased production, such as the possibility of exporting excess rice soon (table 8).

Table 8. Simulated area, production and yield of three rice types in Bangladesh under 15% *Boro* area shifting to MV *Aus*

Items	Season	Clean rice Yield (t/ha)					Area (mha)				
		2009	2015	2020	2025	2030	2009	2015	2020	2025	2030
MV rice varieties	*T. Aus*	2.03	2.33	2.62	2.47	2.93	0.67	0.98	1.06	1.16	1.28
	T. Aman	2.49	3.04	3.08	2.67	3.29	3.85	3.88	3.81	3.92	4.09
	Boro	3.95	4.19	3.75	4.73	4.03	4.57	4.36	4.81	4.91	4.76
LV rice varieties	*T. Aus*	1.23	1.14	1.50	1.51	1.47	0.40	0.33	0.38	0.35	0.42
	T. Aman	1.48	1.78	1.76	1.67	1.88	2.31	2.27	2.10	2.01	2.01
	Boro	2.00	2.12	2.15	2.29	2.30	0.11	0.24	0.09	0.20	0.25
Total production of cleaned rice (mmt)	*T. Aus*	1.86	2.65	3.35	3.39	4.37					
	T. Aman	13.01	15.80	15.43	13.84	17.26					
	Boro	18.26	18.75	18.19	23.71	19.71					
	Total	33.13	37.20	36.98	40.94	41.34					

Source: Author's estimation from simulation.

Simulation result of area, yield and production: scenario 4

After adjusting 5% of area shifted from MV *Boro* area to MV *Aus* and 15% fallow land in the simulation, the total MV *Aus* area will be about 2.02 mha by the year 2030 and total production of clean rice is 40.69 mmt in 2030 (Table 8). The simulated of MV *Aus* area and production increases by shifting 5% MV *Boro* area and fallow land increases the size of MV *Aus* area as well as technological advancement. However, the simulation at combine scenario shows that consistent level of total production is received with the reduced risk with technological advancement in the course of climate change and future market situation. Improved rice varieties and better management can balance production targets and reduce water use by 4725 million liters by 2030.

Table 9. Simulated area, production and yield of three rice types in Bangladesh under scenario 4

Items	Season	Clean rice Yield (t/ha)					Area (mha)				
		2009	2015	2020	2025	2030	2009	2015	2020	2025	2030
MV rice varieties	*T. Aus*	2.03	2.33	2.62	2.47	2.93	0.67	1.60	1.77	1.89	2.02
	T. Aman	2.49	3.04	3.08	2.67	3.29	3.85	3.90	3.82	3.95	4.12
	Boro	3.95	4.19	3.75	4.73	4.03	4.57	3.73	4.11	4.19	4.03
LV rice varieties	*T. Aus*	1.23	1.14	1.50	1.51	1.47	0.40	0.34	0.39	0.36	0.42
	T. Aman	1.48	1.78	1.76	1.67	1.88	2.31	2.29	2.11	2.03	2.03
	Boro	2.00	2.12	2.15	2.29	2.30	0.11	0.24	0.09	0.21	0.25
Total cleaned rice production (mmt)	*T. Aus*	1.86	4.12	5.21	5.22	6.53					
	T. Aman	13.01	15.90	15.50	13.95	17.36					
	Boro	18.26	16.15	15.58	20.29	16.80					
	Total	33.13	36.17	36.28	39.46	40.69					

Source: Author’s estimation from simulation.

On the other hand, about 28 mmt cleaned rice will be needed to feed the population of nearly 190 million by the year 2030 with the decreasing consumption of per capita 146 kg/year (BBS, 2012). A particular portion of remaining amount of about 12.97 mmt by the year 2030 is used for other purposes and stock change. The shift in food habits allows for export access to the global rice market since it reduces rice consumption and consequently creates excess (table 10).

Table 10. Export access, stock change and per capita availability of clean rice in Bangladesh under scenario 4

Items	2009	2015	2020	2025	2030
Export access (mmt)	0	2.92	1.34	1.52	1.55
Stock change (mmt)	2.34	-0.41	-1.91	-1.80	-2.43
Population (million)	144.20	158.96	169.54	180.2	189.85
Per capita availability (kg/yr)	158	207	201	205	205

Source: Author’s estimation from simulation.

Suitable rice varieties for *Aus, Aman* and *Boro* seasons

BRRI has developed 121 high yielding varieties including 8 hybrids of rice for different seasons and for different ecosystems. Among them, some varieties are regarded as for promising *T. Aus*, *T. Aman* and *Boro* rice varieties. Those three table highlighting their growth duration, yield potential, and special characteristics. The *Aus* varieties, such as BRRI dhan65, BRRI dhan83, BRRI dhan83 and BRRI dhan98 etc. are typically short-duration and adaptable to various conditions like drought, salinity, and water-saving cultivation. Along with BRRI dhan65 has a shorter life span than BRRI Dhan43 and BRRI dhan106 and the plants are relatively shorter and tougher so they do not lodge. One of the characteristics of BRRI dhan65 variety is that rice does not easily shatter. The field is very attractive as the flag leaves of this variety are upright and the rice grains are high. The *T. Aman* varieties, including BRRI Hybrid dhan6 and BRRI dhan87, focus on high yield, submergence tolerance, making them suitable for different environments. The *Boro* season varieties, such as BRRI dhan89, BRRI dhan108, BRRI dhan113 and BRRI Hybrid dhan5 etc. emphasize high yield, shorter growth duration, and tolerance to salinity and lodging, ensuring better adaptability and profitability for farmers (BRRI, 2025).

Suitable cropping patterns

All crops are not suitable for everywhere. Some crops are especially suitable for some specific locations. It depends on soil type, land topography and water source. *T. Aus* and *T. Aman* based cropping patterns are the potential alternative with respect to saving water in rice cultivation as these rice cultivations are mainly based on rainfed culture.

Table 11. Ecosystem wise BRRI recommended *T. Aus*-based dominant cropping patterns in Bangladesh

Serial	Ecosystem	Cropping pattern along with varieties/crops
1	Irrigated high land to medium high land	Chickpea-Wet seeded *Aus* (BR26/BRRI dhan48 and 55)-Transplanted *Aman* (BR11, BRRI dhan51)
2	Rainfed high land to medium high land	T. *Aus* (BR26, BRRI dhan48 and 55)-T. *Aman* (BR10, BR11, BR22, BR23, BRRI dhan30, BRRI dhan46, BRRI dhan49)
3	Irrigated Ecosystem (GK Project area)	T. *Aus* (BR26/BRRI dhan48 and 55)-T. *Aman* (BR10, BR11, BR22, BR23, BRRI dhan30, BRRI dhan49)
4	Tidal wetland (Non-saline)	T. *Aus* (BRRI dhan48, BRRI dhan27)-T. *Aman* (BR22, BR23, BRRI dhan44)
5	Rainfed Medium High land (Madhupur tract soil)	T. *Aus* (BR26, BRRI dhan48 and 55)/B. *Aus* (BR21, BR24, BRRI dhan42, BRRI dhan43)-T. *Aman* (BR10, BR11, BRRI dhan30, BRRI dhan49)

Source: BRKB, 2024

List of some ecosystem wise *Aus*-*Aman* based dominant cropping pattern along with varieties/crops are given in Table 11. And some new cropping patterns need to be validated such as Maize-Mungbean-*T. Aus*; Mustard-*T. Aus*-*T. Aman*; Mustard-Mungbean-*T. Aus*-*T. Aman*; Wheat-Fallow-*T. Aman* (saline area); *T. Aman*-Sunflower (saline area).

Table 12. Productivity of some tested alternate cropping patterns in Bangladesh

Serial	Cropping pattern	Rice Equivalent Yield (t/ha)	Reference
1	*Boro*-Fallow-*T. Aman*	11.79	BRRI Annual report 2024
2	Potato-*T. Aus*-*T. Aman*	16.19	BRRI Annual report 2011
3	Mustard-*T. Aus*-*T. Aman*	12.75	BRRI Annual report 2011
4	Maize-Mungbean-*T. Aman*	11.81	BRRI Annual report 2015

The productivity of different alternative cropping patterns is compared in table 12 based on their Rice Equivalent Yield (REY), and it is clear that diversified cropping patterns are more productive than the traditional *Boro*-Fallow-*T. Aman* system. Among the tested patterns, Potato-*T. Aus*-*T. Aman* is found to be most productive, much greater than the others, and Mustard-*T. Aus*-*T. Aman* and Maize-Mungbean-*T. Aman* offer modest gains. The lower REY of the traditional pattern shows that the addition of high-yielding non-rice crops like potato, maize, or mustard can raise productivity as a whole and optimize land use efficiency.

Conclusion

This study shows potentials of shifting or reallocating rice area between the seasons, thereby releasing some land from *Boro* rice cultivation to release intensive water use pressured, Establish these potentials, a number of prerequisites to be looked into BRRI could be able to provide a greater number of highly productive rice varieties and thereby making up scaling of the potential *T. Aus* and *T. Aman* varieties and the improved *T. Aus* and *T. Aman* based cropping pattern in collaboration with DAE, international organizations, BADC, BINA and development partners. Narrowing of the rice yield gap will also be possible by adopting the modern rice production technologies in collaboration with the same. Seed tracking of stress tolerant rice varieties such as BRRI dhan52, BRRI dhan78 and BRRI dhan110 for *T. Aman* and BRRI dhan48, BRRI dhan83, BRRI dhan85, BRRI dhan98 and BRRI dhan106 for *T. Aus* through taskforce activities. Special capacity build-up program for *T. Aus* and *T. Aman* (extension personnel and farmers) and enhancing the regional research and development activities for rice are crucial.

BRRI has plan to develop sustainable rice varieties along with cropping pattern and ecosystem-based production technologies, dry direct seeded aerobic rice along with their production technologies for *Boro* season, development of tidal submergence tolerant rice varieties for *T. Aus* and *T. Aman* seasons for southern region. Increasing *T. Aus* and *T. Aman* rice production needs seed purification of local cultivars and to undertake Balam improvement program for future rice varieties. Strategies have to be framed out for developing high yielding water stagnation and shallow flood (up to 1.0-meter depth) water tolerant varieties for enhancing rice productivity of the concern ecosystem. Crop modeling for the support of future research dimensions and policy in the changing climate scenarios is essential for future strategies. To offset these issues, BRRI will need to conduct scientific assessments before re-allocating *Boro* fields to *T. Aus* cultivation, promote dry-direct seeded aerobic culture, and offer partial irrigation for *Aus* and supplemental irrigation for *T. Aman* rice. In addition, the establishment of short-duration and high-yielding rice varieties, strengthening research collaboration among institutions, and enhancing infrastructure and human resources will be the most important factors in sustaining rice productivity. With such limitations overcome and the recommended solutions implemented, BRRI can elevate rice yield in Bangladesh towards ensuring long-term food security and adapting to environmental hostilities.

Despite strategic planning to expand *T. Aus* and *T. Aman* rice production, several constraints remain that hinder extensive implementation. For the *Aus* season, the high production cost compared to *T. Aman* and *Boro* rice discourages farmers from using its production, with food security issues caused by the lower yield per unit of area of *T. Aus* rice. Additionally, inadequate irrigation facilities, heavy pest and disease prevalence, and lack of short-duration and high-yielding varieties also hinder its development. Similarly, the *T. Aman* season is hampered by restricted irrigation for early transplanting and critical stages, vulnerability to flash floods and unusual submergence, and the lack of high-yielding, tall-seedling varieties that are tolerant to tidal flooding. To address these issues, scientific assessments should be conducted before the replacement of *Boro* fields by *T. Aus* cultivation and shifting towards dry-direct seeded aerobic rice should be promoted. Alternate wetting and drying (AWD) practices, partial and supplementary irrigation, and stressing on short-duration, stress-tolerant rice varieties need to be implemented. Ecosystem-specific cropping calendars, further development of better agronomic packages, and more BRRI-DAE-BINA, international, and private sector collaboration will also be instrumental. Improved infrastructure, increased regional research stations, and the strengthening of human resource capacity will continue to drive the sustainable development of *T. Aus* and *T. Aman* rice production.

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Conflict of interest

The authors honestly declare no conflicts of interest regarding publication of this manuscript.

Authors' contribution

MAS developed the concept and model; accomplished all parts of the manuscript and wrote this manuscript. The author read and approved the final manuscript. Dr. Moin Us Salam provided support to write the manuscripts. KMI and MMH contributed to improve the calibration and write-up of the manuscript.

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