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Seven Decades of Changing Seasonal Land Use for Rice Production in Bangladesh, 1947-2019: Trends, Patterns and Implications

Abstract

Employing Bangladeshi national data on rice production, area and yield disaggregated by dry (irrigated) and wet (rainfed) seasons over a period of 73 years (1947-2019, this paper investigates annual and seasonal dimensions of Bangladeshi rice culture and explores trends, emerging patterns and their implications with a focus on the Green Revolution period since the late 1960s. We find that: (i) structural breaks differ between dry and wet seasons for the same variable or among different variables; (ii) annual and seasonal outputs, areas and yields of overall or HYV rice exhibit slowdown in their increase in the last decade or so; (iii) the diffusion of the HYV rice technology exhibit differential patterns between seasons; (iv) the increasing percentage area under the dry season rice crop has significantly underpinned the increased annual rice yield; and (v) growth in outputs and yields of HYV rice exhibit significant differential patterns by dry and wet seasons.

This is the first long-term study of its kind and contributes to the existing literature in several important ways by (a) investigates rice production in Bangladesh disaggregated by broad crop seasons (dry and wet); (b) identifying structural breaks employing *a priori* reasoning, scatter plots and appropriate econometric tests instead of applying arbitrary cut-off points; and (c) exploring implications of the seasonal dimensions of rice cultivation in Bangladesh.

Keywords: Bangladesh; Green Revolution; Agricultural intensification; Technology diffusion; Seasonal land use; Rice.

JEL Classification: O1, Q0, Q2.

Seven Decades of Changing Seasonal Land Use for Rice Production in Bangladesh, 1947-2019: Trends, Patterns and Implications

1. Introduction and Background

Densely populated and land-scarce Asian rice producing countries have recorded significant transformation in their agriculture over the last five decades or so. This period coincides with the advent of the seed-fertilizer-irrigation technology popularly known as the Green Revolution since the mid-1960s. It has resulted in significant growth in rice output via yield increases, greater dependence on mechanized irrigation, particularly groundwater irrigation, and a considerable increase in the use of inorganic inputs including chemical fertilizers and pesticides. Of late, the agricultural sectors in some countries have also witnessed significant rises in the outputs of high value crops (Brithal et al, 2020). These developments have resulted in greater commercialization of agriculture in Bangladesh and less reliance on semi-subsistence production (BBS, 2020b; Kabir et al, 2017; Osmani et al, 2014).

A characteristic feature of this development process is the occurrence of significant agricultural intensification, that is, more specifically, increased intensity of cropping in both time and space on the same piece of land. This took place in two ways (Andrews and Kassam, 1976, p. 2): (a) sequential cropping with two or more crops per annum; and (b) intercropping with two or more crops grown simultaneously. Both (a) and (b) constitute a process of multiple cropping which takes explicit account of time as a third dimension in crop production making possible “both an increase in area cultivated per year as well as an increase in total yield per unit of area per year” (Dalrymple, 1971, p. 1).

2. Features of Rice in Bangladesh Compared to Other Asian Countries

This paper focuses on land use change in Bangladeshi rice production both from annual and seasonal perspectives over seven decades. As a prelude, we present a brief overview of Bangladesh’s relevant indicators including agriculture and rice intensity, and arable land per capita compared to those of selected Asian rice producing countries between 1965 and 2019. Based on data from FAOSTAT (accessed 29 July 2021), Table 1 presents these indicators. Seven of the nine countries experienced increased agricultural land while this declined marginally for Pakistan and Bangladesh. For Vietnam, arable land almost doubled while the

Philippines, China and Indonesia recorded increases of around 50%. Both Bangladesh and Pakistan witnessed a marginal decline in arable land. The remaining countries recorded some increase but for Sri Lanka it increased by more than 70%. Rice area increased significantly for all countries except in China which recorded a marginal decline. For Pakistan, it more than doubled although from a small base[5].

Bangladesh is by far the most agriculture intensive country with little change in the percentage of agricultural land in total land area. More recently, China has become more agriculturally intensive while India and Pakistan have maintained the same degree of agricultural intensity as that of more than five decades ago. Arable land as a percentage of land area has declined by more than 6% for Bangladesh while India and Pakistan experienced a very minor decline. All the other seven countries registered increases in arable land as a percentage of land area to differing degrees. Bangladesh, India and Pakistan have by far the highest arable land to agricultural land ratio (≥ 80%).

Bangladesh is a highly rice-intensive country. In 2019, Bangladesh had the highest percentage of gross cropped area allocated to rice in relation to its arable land (144.6%, 106.6% in 1965) followed by Vietnam (110.1%, 87.0% in 1965), and the Philippines (83.1%, 64.5% in 1965). For the two most dominant rice-producing countries, China and India, the respective figures were 25.1% (29.8% in 1965) and 28.1% (22.4% in 1965) implying opposite trends in rice intensity (a decrease for China, and an increase for India).

Arable land per capita has declined for all nine countries included in Table 1. As of 2019, it is the lowest for Bangladesh (0.049 ha, 0.158 ha in 1965) followed closely by the Philippines (0.052 ha, 0.156 ha in 1965) and Sri Lanka (0.065 ha, 0.071 ha in 1965) and Vietnam (0.071 ha, 0.147 ha in 1965). Pakistan registered the highest decline in arable land per capita from 0.630 ha in 1965 to 0.144 ha in 2019.

[5] Rice is an export crop, not a staple crop in Pakistan.

Table 1: Land area, agricultural land, arable land, and agricultural and rice intensity in selected rice producing Asian countries, 1965-2019.

Year	Land area (000 ha)	Agricultural land (000 ha)	Arable land (000 ha)	Rice area (000 ha)	Agricultural land as % of land area	Arable land as % of land area	Arable land as % of agricultural land	Rice area as % of arable land	Arable land per capita (ha)
Bangladesh									
1965	13,017	9,637	8,777	9,360	74.0	67.4	91.1	106.6	0.158
2019	13,017	9,397	7,967	11,517	72.2	61.2	84.8	144.6	0.049
China									
1965	942,470	355,509	102,458	30,575	37.7	10.9	28.8	29.8	0.138
2019	942,470	528,509	119,474	29,960	56.1	12.7	22.6	25.1	0.082
India									
1965	297,319	177,177	158,216	35,470	59.6	53.2	89.3	22.4	0.317
2019	297,319	179,578	156,067	43,780	60.4	52.5	86.9	28.1	0.115
Indonesia									
1965	181,157	38,500	18,000	7,327	21.3	9.9	46.8	40.7	0.180
2019	187,752	62,300	26,300	10,678	33.2	14.0	42.2	40.6	0.098
Nepal									
1965	14,300	3,553	1,806	1,111	24.8	12.6	50.8	61.5	0.165
2019	14,335	4,121	2,114	1,492	28.7	14.7	51.3	70.6	0.075
Pakistan									
1965	77,088	37,235	32,080	1,393	48.3	41.6	86.2	4.3	0.630
2019	77,088	36,300	30,507	3,034	47.1	39.6	84.0	9.9	0.144
Philippines									
1965	29,826	8,132	4,820	3,109	27.3	16.2	59.3	64.5	0.156
2019	29,817	12,440	5,590	4,651	41.7	18.7	44.9	83.2	0.052
Sri Lanka									
1965	6,271	2,156	793	432	34.4	12.6	36.8	54.5	0.071
2019	6,186	2,812	1,372	958	45.4	22.2	48.8	69.8	0.065
Viet Nam									
1965	32,549	6,312	5,550	4,826	19.4	17.1	87.9	87.0	0.147
2019	31,343	12,388	6,784	7,470	39.5	21.6	54.8	110.1	0.071

Source: Based on data from FAOSTAT (accessed 29 July 2021).

Globally, Bangladesh is the fourth largest producer of rice after China, India and Indonesia. As a source of food Bangladesh is highly dependent on rice. The per capita annual consumption of rice in Bangladesh in 2016 was 134 kg. (152 kg. in 2010)[6]. This decline notwithstanding, Bangladesh's rice consumption per capita remains more than double that of India, and about

[6] Yunus et al. (2019, p. 8) project a per capita daily rice consumption of 396.6 g for 2018 which translates into an annual figure of 144.8 kg.

1.5 times those of Nepal and Sri Lanka, (Bishwajit et al., 2013). Despite an increase in the diversity of the average Bangladeshi diet in recent years, rice is by far the major component of this diet (BBS, 2017). Although the rate of population growth in Bangladesh has registered a significant decline from 3.01% in 1965, and 2.72% in 1979 to 1.03% in 2020 (https://data.worldbank.org/indicator/SP.POP.GROW?locations=BD, accessed 1 November 2021), the level of population is still rising and likely to reach 216.46 m in 2051 and 223.91 m in 2061 (BBS, 2015, pp.34-35). Given the current population of over 160 million people and current dietary preferences, this implies that it is necessary not only to sustain the current level of rice production but to increase it in line with the predicted rate of rise in Bangladesh's population (Islam and Talukder, 2017; BPC, 2018).

3. Basic Changes in Rice Culture in Bangladesh

Rice culture in Bangladesh has undergone spectacular changes in terms of total output, yield and gross area under cultivation propelled by sequential multiple cropping resulting in a rapid increase in cropping intensity. Yield increase has been by far the main contributor to rice output growth. Rice yield is nearly three times as high as before the Green Revolution (Alauddin et al., 2021). Bangladeshi rice production has been significantly underpinned by the expansion of the dry season area under rice cultivation due primarily to the rapid expansion of the availability of high yielding varieties (HYVs) of rice and due to irrigation (increasingly from groundwater sources). This is consistent with a similar pattern in other South Asian countries.

Alauddin et al., (2021) used sixty years (1960-2019) of aggregate annual rice yield data and employed graphical methods and econometric tests to locate structural breaks in the time series. Alauddin et al., (2021, p.344) identified a slowdown in annual rice yield increase with the yield becoming almost stationary in the last phase (2010-2019). The use of annual data, however, masks seasonal diversity.

Rahman (2010) examined agricultural land use change in Bangladesh over six decades (1948-2006) and identified four phases: (1) Pre-Green Revolution (1948-1959), (2) Early Green Revolution (1960-1975), (3) Take-off Green Revolution (1976-1985), and (4) Mature Green Revolution (1986-2006). While Rahman's broad categorization of time phases appear logical one needs to exercise caution in using them even though elements of the Green Revolution like mechanized irrigation e.g., low lift pumps (LLPs), shallow tube wells (STWs), and deep tube wells (DTWs), and chemical fertilizers were introduced in the early 1960s[7]. However, it was not until the late 1960s when HYVs of rice were introduced that the use of fertilizers and irrigation technologies assumed any real significance (Alauddin and Tisdell, 1991, p.7). Therefore, the period until the mid-1960s (circa 1965 or 1966) could be treated as the pre-Green Revolution period. Similarly, mid-1990s onwards is a more appropriate beginning of the mature Green Revolution phase (Alauddin et al, 2021, p.344). We also argue against the use of uniform structural breaks for all variables given that their turning points may occur at different points in time.

4. The Main Purpose and the Contribution of this Paper

In this paper a comprehensive examination of seasonal dimensions of Bangladeshi rice culture is undertaken to explore trends, emerging patterns and their implications. We focus on changing seasonal land use pattern in Bangladeshi rice production.

We employ Bangladeshi national data on rice production, area and yield disaggregated by dry (irrigated) and wet (rainfed) seasons over a period of 73 years (1947-2019). We also focus on the period of new technology (1968-2019). We address the following relevant research questions:

- Do structural breaks differ between dry and wet seasons for the same variable or among different variables?
- Do annual and seasonal outputs, areas and yields of overall or HYV rice exhibit any slowdown in any time phase?
- Does the diffusion of the HYV rice technology exhibit differential patterns between seasons?
- To what extent does the percentage area under the dry season rice crop to the total rice area affect annual rice yield?
- Does growth in outputs and yields of HYV rice exhibit differential patterns by seasons?

This paper contributes to the existing literature in several important ways. It is the first long-term study which:

- Investigates rice production in Bangladesh disaggregated by season (dry and wet).

[7] These technologies did not feature prominently in the (Pakistan) government's agricultural development strategy in the 1950s (see e.g., Huq, 1963; Papanek, 1967).

- Identifies differential structural breaks employing *a priori* reasoning, scatter plots and appropriate econometric tests instead of applying arbitrary cut-off points.
- Explores policy implications of the seasonal dimensions of rice cultivation in Bangladesh.

The remainder of this paper is organized as follows. Section 5 outlines materials and methods followed by results in Section 6. Section 7 discusses the results. Section 8 explores eco-environmental implications of the process. Section 9 concludes the paper.

5. Materials and Methods

5.1 Data sources and variable definition

Data sources and variable definition

The basic data for annual and seasonal rice output, area, and yield, spread of HYVs of rice, irrigation, and cropping intensity were sourced from: *Agricultural Production Levels of Bangladesh 1947-1972*; *Forty-five years of Agricultural Statistics of Major Crops;* various issues of the *Yearbook of Agricultural Statistics of Bangladesh* (all published by the Bangladesh Bureau of Statistics). Where relevant and appropriate, inconsistencies were cross checked using information from: Hamid (1991); and relevant issues of *Monthly Statistical Bulletin of Bangladesh*, and *Statistical Yearbook of Bangladesh* (published by the Bangladesh Bureau of Statistics).

The discussion of results in Section 7 and matters relating to eco-environmental effects in Section 8 necessitated additional information from sources which have been cited with due attributions. Appendix Table 1 sets out a brief description of the rice crop calendar, and variable definitions.

5.2 Analytical Frameworks

This study employs three different analytical frameworks: (a) graphical representation and econometric tests to identify structural breaks within a time series; (b) linear regression with dummy variables employing a robust standard error model to estimate trends in total annual and seasonal areas under rice, its yields and outputs in different time phases; and (c) a logistic growth model to investigate the diffusion trajectory of HYV technology in the dry and wet seasons over time.

Structural breaks

Identification of structural breaks in all the time series variables required a two-stage approach. First, two-way scatter plots with the target variables on the vertical axis and time on the horizontal axis provide an approximate idea of some probable break points to locate discontinuities/structural breaks e.g., a pronounced jump/dip at a point in time (Asteriou & Hall, pp. 17-18). Second, from the graphs, one can select some alternative break points and then use the Wald test to confirm whether they concur with the graphical displays (Asteriou and Hall 2015, pp. 219-220). The Wald test requires regressing the target variables against time and obtaining the χ^2 test statistic. The rejection of the null hypothesis of no structural breaks at $p<.05$ confirms any structural breaks.

5.3 Regression model specification

Time trends using dummy variables

We postulate a regression model for the time series data on different variables for the 1947-2019 period (entire time) or 1968-2019 (the period of new technology). It is quite reasonable to expect different trajectories over these periods. One segment of the time series might show an upward trend, while in another segment it might show a downward trend or a flatter path. Therefore, the regression lines for different segments of the time series are likely to differ both in intercept and slope (Gujarati, 2015). Different factors including pace of technology diffusion, scientific breakthroughs, demographic factors, and significant change in public policy discourse might underlie these time trajectories.

We now specify the following regression model with ***Y*** as the dependent variable and time (***T***) as the independent variable. This is a general form which can be extended to crop area, output, and yield.

$$Y = \alpha_1 + \beta_1 T + \alpha_i D_{Ti} + \beta_i D_{Ti} T + u_T \quad (1)$$

Where

$i = 2, \ldots n$, n being the number of phases within the time series.

α_1 and β_1 respectively represent the trend line intercept and slope for the reference period while α_i and β_i respectively denote intercept and slope for Phase *i* relative to those for the reference period.

D_{Ti} is the dummy variable, 1 for Phase *I* observations, 0 otherwise

u_T is the random disturbance term

T = 1, 2, …, 73 for 1947, 1948, …, 2019 (entire period) or T = 1, 2, …, 52 for 1968, 1969, …, 2019 (Green Revolution period).

The estimated equations for different phases can be stated as:

$$\text{Phase 1 (reference phase): } \hat{Y} = \hat{\alpha}_1 + \hat{\beta}_1\, T \qquad (2)$$

$$\text{Phase } i\text{: } \hat{Y}_i = (\hat{\alpha}_1 + \hat{\alpha}_i) + (\hat{\beta}_1 + \hat{\beta}_i)\, T \qquad (3)$$

To address the very common OLS problems of violation of constant error variance (heteroscedasticity) and non-independence of error (autocorrelation), we applied the heteroscedasticity and autocorrelation consistent (HAC) standard errors procedure to find the unbiased and consistent estimators (Gujarati, 2015, pp. 125-128; Wooldridge, 2020, pp. 419-420).

Logistic model

It is widely documented in the relevant literature that the technology diffusion process does not follow a linear path. Logistic models are commonly used to investigate diffusion of innovations (e.g., Griliches, 1957; Dixon, 1980). Equation (4) specifies the logistic growth model where the growth curve reaches a limit (asymptote) with time (T) as the explanatory variable.

$$Y(T) = \frac{\beta_1}{(1+\exp\,(-\beta_2 * (T - \beta_3))} \qquad (4)$$

Where

Y = percentage area planted with HYVs in wet (or dry) season in total (wet or dry season) rice area.

β_1 = the ceiling or equilibrium value or carrying capacity of the environmental conditions

$\beta_2 =$ the rate of growth coefficient

$\beta_3 =$ the constant

As $T \longrightarrow \infty$, $Y \longrightarrow \beta_1$

6. Results

We present the results in two segments. Section 6.1 focuses on the entire 73-year period with an in-depth investigation of the dry and wet season components of land use in rice. Section 6.2 focuses exclusively on the period of the Green Revolution technology (1968-2019).

6.1 The 1947-2019 period

Table 2 presents the time trends in annual and seasonal rice yields kg ha^{-1} for the 1947-2019 period. The scatter plots of these three variables are portrayed in Figure 1. Based on visual observations and the Wald test (p<.01), four phases are identified for all three variables. All the equations have an explanatory power of ≥ 0.98, and the estimated parameters of the trend dummy variables are statistically significant except for the last phase (2007–2019) in the case of the dry season yield. Wet season and annual rice yields displayed similar trajectories in terms of structural breaks. The first structural breaks for both occur in the early 1980s in contrast to the first structural break for the dry season in 1967. Given that the dry season rice area as a percentage of total annual rice area was ≤5% until the mid-1960s crossing 6% in 1966 but remained < 10% until 1980, any change in the dry season area by way of expanding the HYV area (further details in Section 6.2) is likely to influence the time trajectory for dry season rice yields in a more pronounced way.

On the other hand, given that the wet season was the main rice crop season with ≥80% of the rice area until 1987, it took longer for HYVs to spread during this season, yield effect did not manifest until much later than for the dry season crop. The annual and dry season rice yield absolute increase peaked at 65 kg ha^{-1} and 71 kg ha^{-1} in the decade beginning late 1990s before slowing down to about 46 and 29 kg ha^{-1} in their respective last phases (2007-2019 and 2009-2019). The wet season rice yields in contrast rose steadily in all phases without any slowdown. By the last phase (2010-2019), it exceeded 40 kg ha^{-1} from 28 kg ha^{-1} during 1999-2009. This notwithstanding, both annual and dry season rice yields have consistently been higher than that for the wet season and the gap seems to be widening albeit marginally.

Table 2: Trends in annual and seasonal yields of rice per hectare of gross area cropped with rice (kg ha^{-1}) in different phases, Bangladesh 1947-2019

Annual rice yield (R^2 = 0.9931; F – statistic (7, 65) = 2492.26; N = 73)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy 2, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1947-1983	1984-1998	1999-2008	2009-2019	1947-1983	1984-1998	1999-2008	2009-2019
848.03^{***}	-772.14^{***}	-2230.76^{***}	-990.54^{***}	10.98^{***}	23.45^{***}	54.51^{***}	35.17^{***}
Estimated regression models for various phases (annual rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1947-1983	1984-1998	1999-2008	2009-2019	1947-1983	1984-1998	1999-2008	2009-2019
848.03	75.89	-1382.73	-142.51	10.98	34.43	65.49	46.16
Dry season rice yield (R^2 = 0.9893; F – statistic (7, 65) = 1653.51; N = 73)							
1947-1966	1967-1996	1997-2006	2007-2019	1947-1966	1967-1996	1997-2006	2007-2019
857.56^{***}	458.20^{***}	-1596.23^{***}	1158.48^{***}	21.54^{***}	5.25	49.27^{***}	7.19
Estimated regression models for various phases (dry season rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1947-1966	1967-1996	1997-2006	2007-2019	1947-1966	1967-1996	1997-2006	2007-2019
857.56	1315.76	-738.67	2016.04	21.54	26.79	70.81	28.73
Wet season rice yield (R^2 = 0.9801; F – statistic (7, 65) = 1299.92; N = 73)							
1947-1982	1983-98	1999-2009	2010-2019	1947-1982	1983-1998	1999-2009	2010-2019
881.97^{***}	-298.37^{*}	-674.08^{*}	-1289.73^{***}	6.60^{***}	10.60^{***}	21.44^{***}	33.91^{***}
Estimated regression models for various phases (wet season rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1947-1982	1983-98	1999-2009	2010-2019	1947-1982	1983-98	1999-2009	2010-2019
881.97	583.61	207.89	-407.76	6.60	17.20	28.04	40.50

$^{***}p < .01$; $^{*}p < .10$

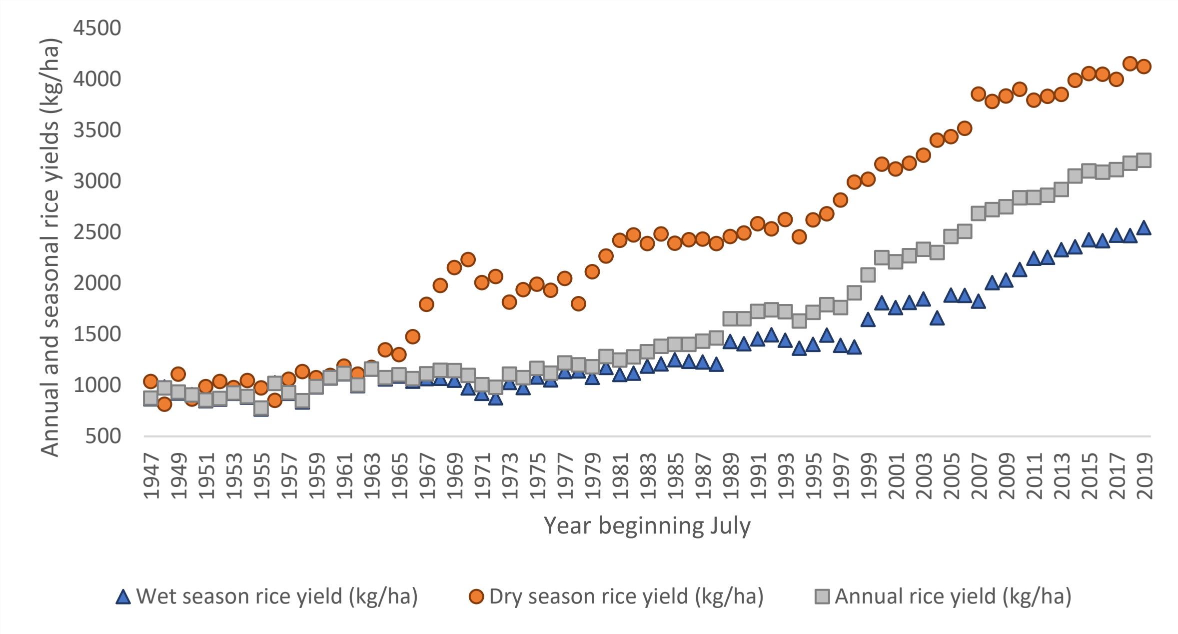

Figure 1: Trends in annual and seasonal rice yields in various phases, Bangladesh 1947-2019.

Table 3 presents the trends in percentage of total annual land area allocated to dry and wet season rice crops with four structural breaks (Figure 2). The structural breaks are identical for both the wet and dry seasons. This is logical given that they use the common denominator (total annual rice area). The first break occurs in 1967, the beginning of the Green Revolution manifesting in rapid expansion of area under dry season rice via irrigation.

The share of dry season area in annual rice area increased steadily over the years. It experienced an accelerated pace of growth during the two phases encompassing three decades to 1997. During 1998-2019 the percentage area under dry season increased steadily from a low of 30% to stabilize around the low 40% mark in the last decade or so. In the same period, the wet season's share experienced a corresponding decline overall stabilizing at around the high 50% mark. Thus, the wet season remains dominant in terms of rice area.

Table 3: Trends in land areas allocated to rice in dry and wet seasons as percentages of annual land area cropped with rice in different phases, Bangladesh 1947-2019

Dry season rice area as a % of annual area cropped with rice (R^2 = 0.9932; *F* – statistic (7, 65) = 3074.94; *N* = 73)							
Intercept, $\hat{\alpha}_1$	Intercept dummy 1, $\hat{\alpha}_2$	Intercept dummy 2, $\hat{\alpha}_3$	Intercept dummy 3, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1947-1967	1968-1987	1988-1997	1988-2019	1947-1967	1968-1987	1988-1997	1988-2019
3.53^{***}	-3.30^{*}	-2.68	-3.82	0.09^{***}	0.24^{***}	0.41^{***}	0.40^{***}
Estimated regression models for various phases (dry season % area)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), *i* = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), *i* = 2,., 4**			
1947-1967	1968-1987	1988-1997	1988-2019	1947-1967	1968-1987	1988-1997	1988-2019
3.52	0.22	0.83	-7.34	0.09	0.33	0.50	0.49
Wet season rice area as a % of annual area cropped with rice (R^2 = 0.9932; *F* – statistic (7, 65) = 3074.94; *N* = 73)							
1947-1967	1968-1987	1988-1997	1998-2019	1947-1967	1968-1987	1988-1997	1998-2019
96.49^{***}	3.30^{*}	2.68	3.82	0.09	-0.24^{***}	-0.41^{***}	-0.40^{***}
Estimated regression models for various phases (wet season % area)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), *i* = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), *i* = 2,., 4**			
1947-1967	1968-1987	1988-1997	1998-2019	1947-1967	1968-1987	1988-1997	1998-2019
96.49	99.78	99.17	92.66	-0.09	-0.37	-0.5094	-0.49

$^{***}p < .01$; $^{*}p < .10$

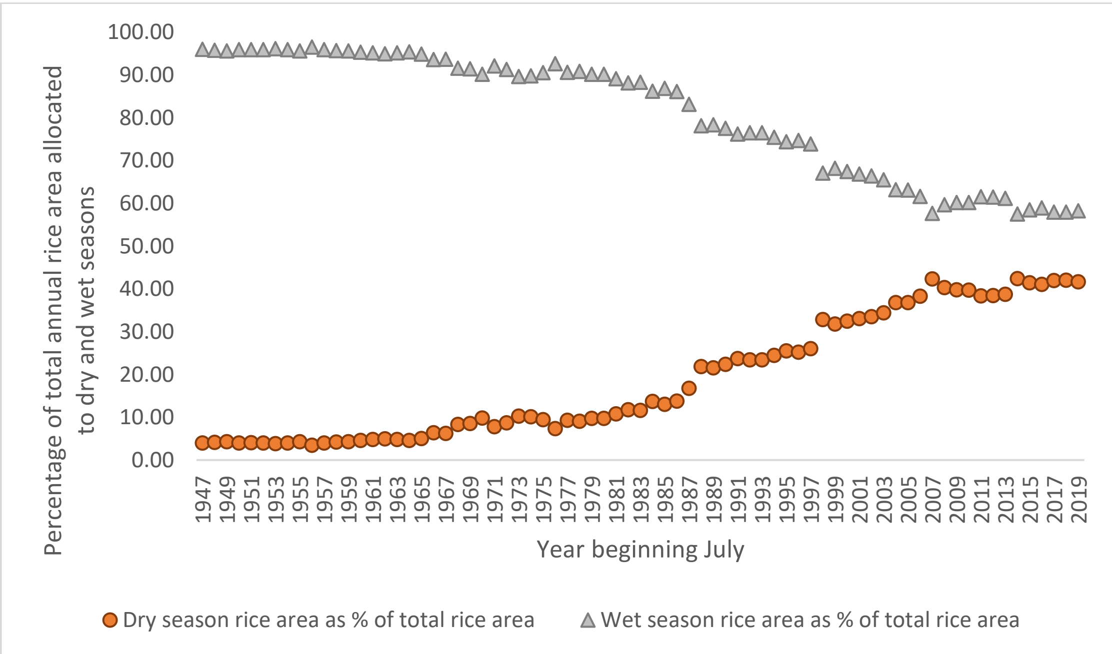

Figure 2: Trends land areas allocated to rice in dry and wet seasons as percentages of annual land area cropped with rice in different phases, Bangladesh 1947-2019.

Table 4 sets out trends in seasonal rice outputs as percentages of annual rice output in various phases while Figure 3 presents their scatter plots. Growth in the share of dry season rice peaked during 1987-1997. It grew at a considerably slower rate during 1998-2019. A corresponding decline in the wet season's output share occurred. By 2004, the dry season's contribution to the annual rice output exceeded 50%. More recently, its share has stabilized in the mid-50% range making the dry season the dominant rice season in terms of output.

Table 4: Trends in seasonal rice outputs as percentages of annual rice output in various phases, Bangladesh 1947-2019

Dry season rice output as a % of annual rice output (R^2 = 0. 9857; F – statistic (7, 65) = 1267.76; N = 73)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
3.36***	1.97	-9.80	28.81***	0.17***	0.25**	0.74***	0.15
Estimated regression models for various phases (dry season % output)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
3.36	5.32	-6.44	32.16	0.17	0.42	0.91	0.32
Wet season rice output as a % of annual rice output R^2 = 0.9932; F – statistic (7, 65) = 3074.94; N = 73)							
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
96.67***	-1.97	9.80	-28.81***	-0.17***	-0.25**	-0.74***	-0.15
Estimated regression models for various phases (wet season % output)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
96.67	94.71	106.47	67.87	-0.17	-0.42	-0.91	-0.32

*** p < .01; ** p < .05.

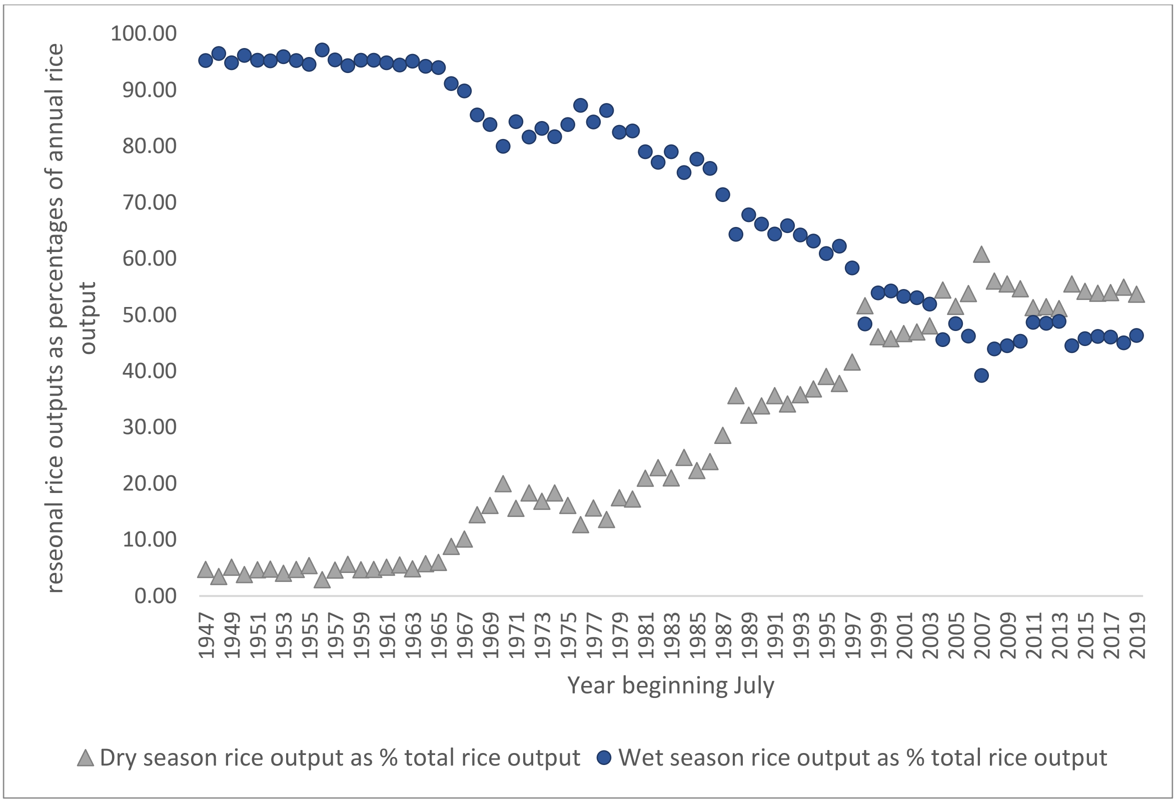

Figure 3: Trends seasonal rice outputs as percentages of total annual rice output in various phases, Bangladesh 1947-2019.

Table 5 presents the time trajectory of the annual and seasonal rice outputs. Structural breaks for the wet season and annual rice output levels are identical. Dry season rice output displays different structural breaks except for the last decade or so. This is not surprising given that for much of the time series, the overall rice output has been influenced more by the wet season component, while the dry season output grew rapidly from a small base.

Dry season rice output grew steadily over all the phases. However, it peaked during the 1998-2007 period with an annual increase of ≈ 664,000 tonnes before slowing down to an increase of ≈ 258,000 tonnes annually during 2008-2019. The annual rice output followed a similar path to the one for the dry season. It peaked with an annual increase of 654,000 tonnes during 1975-2008 slowing down somewhat to 542,000 tonnes during 2009-2019. The wet season rice output registered annual increases in all phases with a slowdown to 32,000 tonnes annually during 1975-2008 but accelerating to > 228,000 tonnes during 2009-2019.

Table 5: Trends in annual and seasonal outputs of rice (000 MT) in different phases, Bangladesh 1947-2019

Annual rice output (R^2 = 0.9910; F – statistic (7, 65) = 1011.61; N = 73)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1947-1959	1960-1974	1975-2008	2009-2019	1947-1959	1960-1974	1975-2008	2009-2019
6106.20***	-1182.78**	-16808.24	-8995.85***	213.92***	80.12***	440.52**	327.98***
Estimated regression models for various phases (annual rice output)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1959	1960-1974	1975-2008	2009-2019	1947-1959	1960-1974	1975-2008	2009-2019
6106.20	4923.42	-10702.04	-2889.65	213.92	294.04	654.44	541.90
Dry season rice output (R^2 = 0.9904; F – statistic (7, 65) = 1013.01; N = 73)							
1947-1983	1984-1997	1998-2007	2008-2019	1947-1983	1984-1997	1998-2007	2008-2019
-399.24***	-7778.50***	-24030.04**	1186.01	87.31***	231.39***	576.68***	170.79**
Estimated regression models for various phases (dry season rice output)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1983	1994-1997	1998-2007	2008-2019	1947-1983	1994-1997	1998-2007	2008-2019
-399.24	-8177.74	-24429.28	786.77	87.31	318.70	663.99	258.10
Wet season rice output (R^2 = 0.9359; F – statistic (7, 65) = 557.83; N = 73)							
1947-1959	1960-1974	1975-2008	2009-2019	1947-1959	1960-1974	1975-2008	2009-2019
6807.21***	1065.81	4014.94***	-6614.98***	46.83	28.02	-14.88***	181.44***
Estimated regression models for various phases (wet season rice output)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1959	1960-1974	1975-2008	2009-2019	1947-1959	1960-1974	1975-2008	2009-2019
6807.21	7873.02	10822.14	192.23	46.83	74.85	31.95	228.27

$^{***}p < .01$; $^{**}p < .05$.

Table 6 presents trends in annual and seasonal areas cropped with rice. The structural breaks for the first two phases of the dry (1947-1967 and 1968-1986) and wet (1947-1970 and 1971-1987) season areas are similar. The last two phases for the two seasons, however, show contrasting patterns. The third phase for the dry season (1987-1997) is shorter than the corresponding phase of the wet season (1988-2003) while the opposite is the case for the last phases of the two seasonal areas (dry season 1998-2019; wet season 2004-2019).

Gross annual rice area increased in all phases (peaking during the 1960-1970 phase with about 160,000 ha annually) then increased at a slower pace respectively by ≈ 20,000 and 9,000 ha per annum during 1971-1987 and 1988-2019. The dry season area increased in all phases peaking at 65,000 ha annually during 1987-1997. In the last phase (1998-2019) it recorded a marginally slower pace of annual increase (58,000 ha).

The wet season area after increasing (by ≈ 68,000 ha per year) during 1947-1970, declined in all subsequent phases. The 1988-2008 phase recorded the strongest annual decline (≈ 95,000 ha) while in the last phase (2004-2019) it declined at a much slower pace(19,000 ha). The overall annual rice area appears to have stabilized around 11.5 m ha with the wet season area hovering about 6.6 m ha and the dry season area just below 5 m ha.

Table 6: Trends in annual and seasonal areas cropped with rice (000 ha) in different phases, Bangladesh 1947-2019

Annual rice area (R^2 = 0.9530; F – statistic (7, 65) = 228.53; N = 73)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Time trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1947-1959	1960-1970	1971-1987	1988-2019	1947-1959	1960-1970	1971-1987	1988-2019
7914.76***	-1635.90***	3177.14***	2780.29***	45.70***	113.90***	-25.85**	-36.46**
Estimated regression models for various phases (annual rice area)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1959	1960-1970	1971-1987	1988-2019	1947-1959	1960-1970	1971-1987	1988-2019
7914.76	6278.87	11091.91	10695.06	45.70	159.59	19.85	9.24
Dry season rice area (R^2 = 0.9916; F – statistic (7, 65) = 2627.56; N = 73)							
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
263.41***	-328.29***	-696.25	410.36	11.17***	28.78***	54.14***	46.97***
Estimated regression models for various phases (dry season rice area)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1967	1968-1986	1987-1997	1998-2019	1947-1967	1968-1986	1987-1997	1998-2019
263.41	-64.89	-432.85	673.76	11.17	39.96	65.31	58.14
Wet season rice area (R^2 = 0.9613; F – statistic (7, 65) = 295.19; N = 73)							
1947-1970	1971-1987	1988-2003	2004-2019	1947-1970	1971-1987	1988-2003	2004-2019
7249.35***	4038.68***	5382.46***	606.63	67.92***	-97.92***	-162.58***	-87.45***
Estimated regression models for various phases (wet season rice area)							
Intercept ($\hat{\alpha}_1$ + $\hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1$ + $\hat{\beta}_i$), i = 2,., 4**			
1947-1970	1971-1987	1988-2003	2004-2019	1947-1970	1971-1987	1988-2003	2004-2019
7249.35	11288.03	12631.81	7855.98	67.92	-29.99	-94.66	-19.53

*** p < .01; ** p < .05.

At this stage, it can be hypothesized that dry season rice expansion via irrigation and HYV diffusion has been the primary factor underlying the growth in rice output and yield on an annual basis. Thus, we can pose a question: Is there any association between land allocated to dry season rice as a percentage of the gross area allocated to rice and the annual yield of rice?

We have addressed this question by regressing annual rice yield (*AYLD*) against the percentage of annual rice land allocated to dry season rice (*DSPCA*) for the 73-year period. After trying different functional forms e.g., including a linear function, a function with dummy variables and an exponential one, we finally settled on the quadratic form based on its explanatory power, and significance of the estimated parameters (Equation 5).

$$\widehat{AYLD} = 937.08^{***} + 10.6255\ DSPCA^{**} + 0.9123\ DSPCA^{2***} \qquad (5)$$

$(R^2 = 0.9723;\ F\ (2{,}70) = 868.22;\ N{=}73;\ ^{***}p < .01;\ ^{**}p < .05)$.

Thus, the percentage of annual rice land allocated to dry season rice area is a significant correlate of annual rice yield.

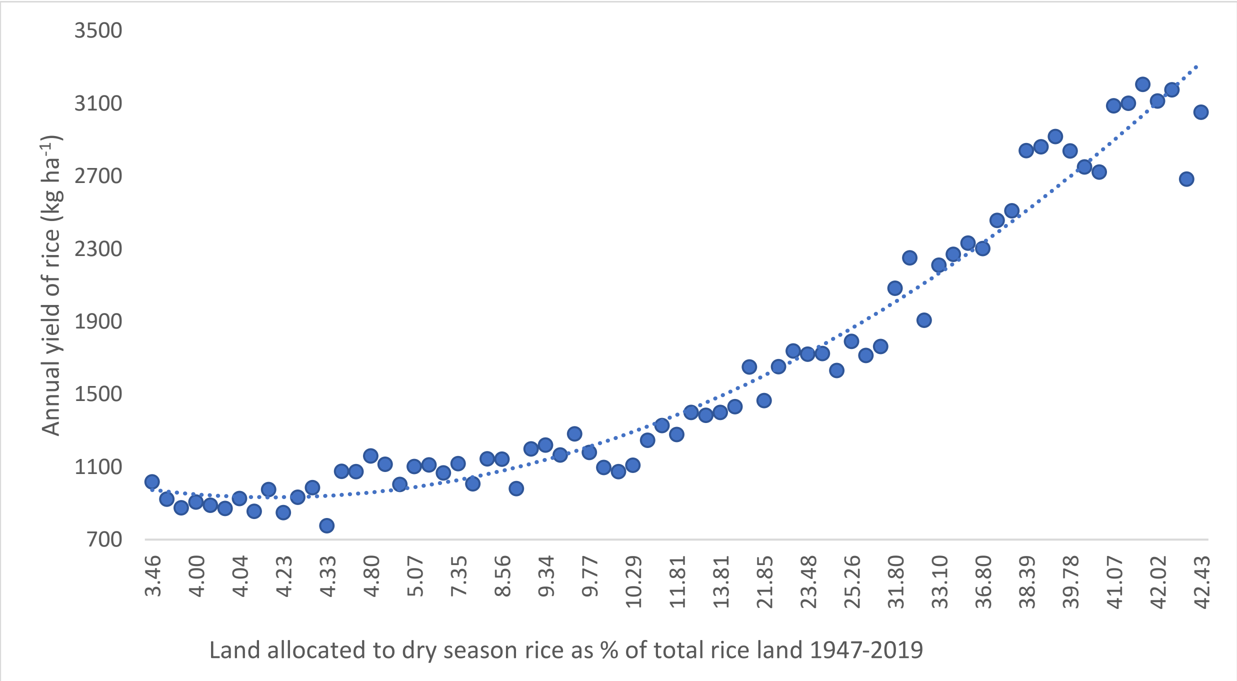

Figure 4: Relationship between annual yield of rice and percentage of annual rice land allocated to dry season rice area, Bangladesh 1947-2019.

6.2 *The 1968-2019 period*

Table 7 presents, and Figure 5 illustrates trends in annual and seasonal areas under HYVs of rice in different phases during 1968-2019. The structural breaks for annual and dry season areas under HYV rice cultivation are similar. On the other hand, wet season structural breaks are quite different except for the last phase.

The annual area under HYV rice rose annually by 158,000 ha during 1968-1985 and accelerated to 217,000 ha during 1986-1997. This annual increase slowed down to 209,000 ha per annum during 1998-2007 and further to 127,000 ha during 2008-2019. The dry season HYV area increased by 60,000 ha per annum during 1968-1986 accelerating to ≈ 74,000 ha and 85,000 ha respectively during 1987-1997 and 1998-2005. During 2006-2019 the area under dry season HYV rice expanded at a declining annual rate of ≈ 35,000 ha.

The wet season HYV area increased annually in all phases. However, the pace of increase followed a U-shaped path with ≈ 113,000 ha during 1968-1978, declining to ≈75,000 ha during 1979-1990, then increasing to ≈ 84,000 and 94,000 ha during 1991-2007 and 2008-2019 respectively.

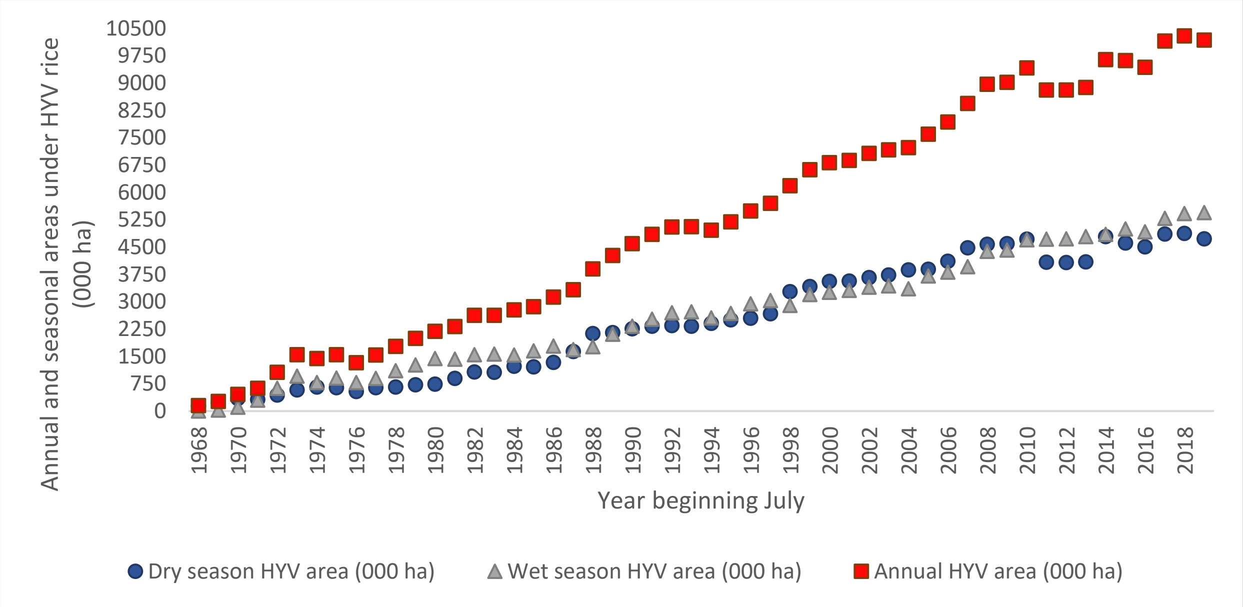

Figure 5: Trends annual and seasonal areas under HYV rice (000 ha), Bangladesh 1968-2019.

Table 7: Trends in annual and seasonal areas under HYV rice (000 ha) in different phases, Bangladesh 1968-2019

Annual HYV rice area (R^2 = 0.9952; F – statistic (7, 44) = 1586.92; N = 52)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy 2, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1968-1985	1986-1997	1998-2007	2008-2019	1968-1985	1986-1997	1998-2007	2008-2019
113.71	-789.96	-349.20	3433.40	158.61***	58.02***	50.65**	-31.89
Estimated regression models for various phases (annual HYV rice area)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1985	1986-1997	1998-2007	2008-2019	1968-1985	1986-1997	1998-2007	2008-2019
113.71	-676.25	-231.49	3547.11	158.61	216.63	209.25	126.72
Dry season HYV rice area (R^2 = 0.9914; F – statistic (7, 52) = 2694.05; N = 52)							
1968-1986	1987-1997	1998-2005	2006-2019	1968-1986	1987-1997	1998-2005	2006-2019
111.29***	335.94	577.04**	2816.79***	60.04***	14.22	25.09***	-25.29**
Estimated regression models for various phases (dry season HYV rice area)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1986	1987-1997	1998-2005	2006-2019	1968-1986	1987-1997	1998-2005	2006-2019
111.29	447.23	688.33	2928.08	60.04	74.26	85.13	34.75
Wet season HYV rice area (R^2 = 0.9947; F – statistic (7, 44) = 1566.35; N = 52)							
1968-1978	1979-1990	1991-2007	2008-2019	1968-1978	1979-1990	1991-2007	2008-2019
-82.84	443.48**	530.94**	626.59*	112.61***	-37.21**	-28.17**	-19.10
Estimated regression models for various phases (wet season HYV area)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1978	1979-1990	1991-2007	2008-2019	1968-1978	1979-1990	1991-2007	2008-2019
-82.84	360.64	448.10	543.75	112.61	75.40	84.44	93.51

$^{***}p < .01$; $^{**}p < .05$; $^{*}p < .10$.

Figure 6 illustrates the time paths of percentage areas under HYVs of rice in dry and wet seasons in their respective total areas since 1968. As documented in the literature (e.g., Griliches, 1957; Dixon, 1980), the diffusion process does not follow a linear path. Therefore, a logistic or Gompertz function is likely to be appropriate. For this study, we fitted both curves to the observed data but did not find any difference in terms of goodness of fit or the significance of the parameters or the time trajectory. We present the results based on the logistic functions illustrated in Figure 6.

Regressing the percentage of HYV area in total dry season rice area (Y) against time (T), Equation (6) presents the estimated logistic model:

$$\hat{Y} = \frac{\hat{\beta}_1}{(1+\exp(-\hat{\beta}_2*(T-\hat{\beta}_3)))} = \frac{97.2424}{(1+\exp(-0.1533*(T-8.3147)))} \qquad (6)$$

(R^2 = 0.9982; *N=52;* $\hat{\beta}_1, \hat{\beta}_2$ and $\hat{\beta}_3$ significant at p <. 01).

Equation (7) presents the estimated logistic regression model for HYV percentage area in total wet season rice (Y) against time (T):

$$\hat{Y} = \frac{\hat{\beta}_1}{(1+\exp(-\hat{\beta}_2 * (T-\hat{\beta}_3)))} = \frac{103.8584}{(1+\exp(-.0866*(T-36.7941))} \quad (7)$$

(R^2 = 0.9975; N=52; $\hat{\beta}_1, \hat{\beta}_2$ and $\hat{\beta}_3$ significant at p <. 01).

The dry and wet season HYV percentage areas demonstrate the contrasting time trajectories of diffusion. The dry season percentage area increased faster than that of the wet season and by 1993, 90% (2.3 m ha) of the total dry season rice area was under HYVs. The marginal addition to dry season rice area was all due to the expansion of HYVs.

On the other hand, 2.7 m ha of HYV area under wet season rice accounted for ≈ ⅓ of the total wet season rice area in 1993. Thus, of the 5 m ha of the total HYV rice area, 54% was accounted for by the wet season HYV rice component in 1993. In later years when the total wet season rice area (HYVs and non-HYVs) steadily declined from 8.4 m ha in 1993 before stabilizing around 6.6 m ha in the last decade or so, the absolute increase in wet season HYV area at the margin made a greater impact on the diffusion rate due to the declining denominator. Hence, the steeper slope of the wet season diffusion curve in the last 25 years or so. By 2019, the wet season HYVs covered nearly 82% of its total rice area. With increased availability of irrigation, the dry season rice area increased with the HYV rice area increasing correspondingly.

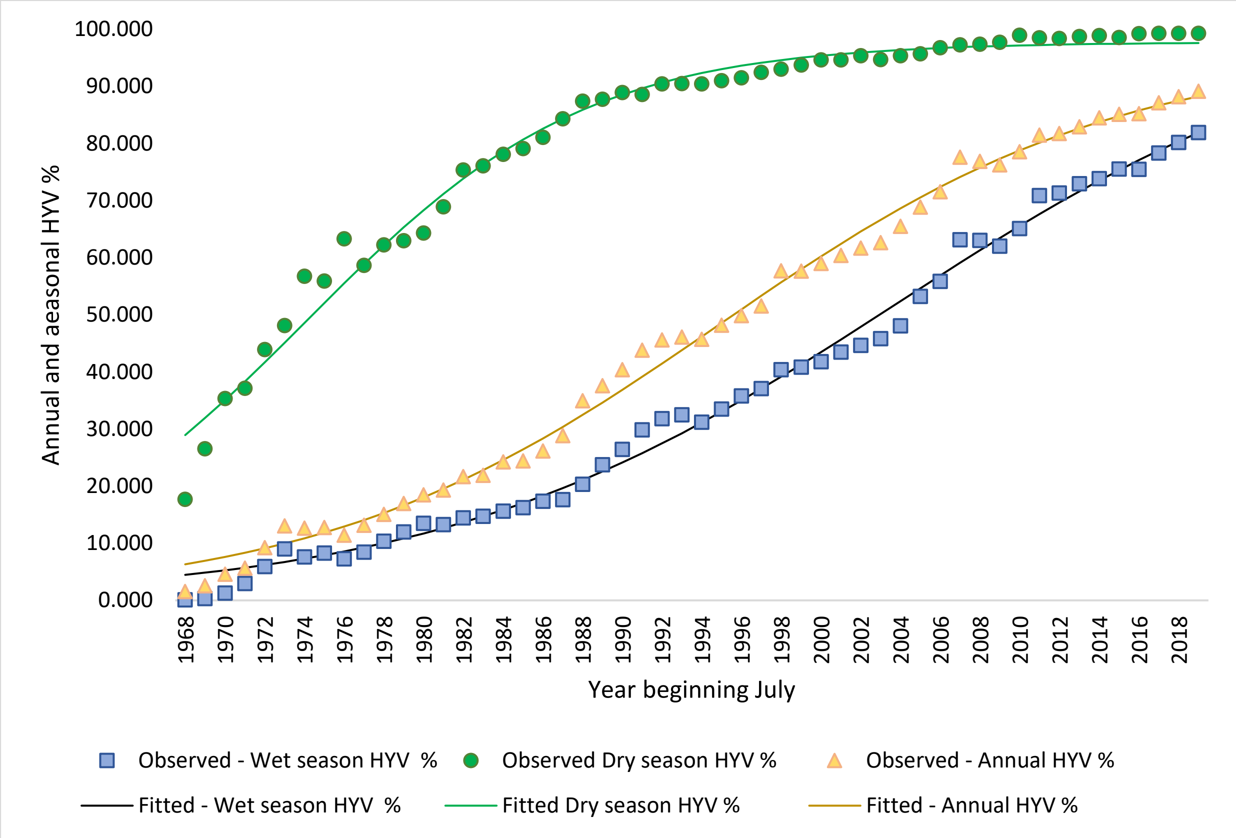

Figure 6: Time trajectories of diffusion of HYVs of rice seasonally and annually, Bangladesh 1968-2019.

Considering the above, it is worthwhile posing a question: How does the time trajectory of the HYV percentage area in total annual rice area compare with the seasonal scenarios? Equation (8) presents the relevant estimated logistic regression model for the HYV percentage area in total annual rice area (Y) against time (T):

$$\hat{Y} = \frac{\hat{\beta}_1}{(1+\exp(-\hat{\beta}_2 * (T-\hat{\beta}_3)))} = \frac{96.3077}{(1+\exp(-.0990*(T-27.8207)))} \tag{8}$$

($R^2 = 0.9985$; $N=52$; $\hat{\beta}_1, \hat{\beta}_2$ and $\hat{\beta}_3$ significant at $p <. 01$).

Three diffusion curves illustrated in Figure 6, indicate that during:

- 1968-2019 annual HYV percentage area has a stronger association with the one for the wet season (r = 0.989, p<.01) than with dry season HYV percentage area (r = 0.874, p<.01).

- 1968-1993, the association between the annual and dry season HYV percentages is stronger than during 1968-2019 (r = 0.918, p<.01) but still somewhat weaker than its association with the wet season HYV percentage area (r = 0.994, p<.01).
- 1994-2019, the strengths of these associations become almost identical (wet season r = 0.992, p<.01; dry season r = 0.985, p<.01).

Table 8 presents the trends in annual and seasonal outputs of HYV rice in different phases. The structural break points are quite similar in all three cases (Figure 7). Dry season HYV rice output increased annually in all phases, by ≈152,000 MT during 1968-1986 rising to 258,000 MT during the next decade and peaked at 532,000 MT during 1998-2006. The last phase (2007-2019) recorded a slowdown in its annual increase to 231,000 MT. The annual HYV rice output followed a similar time path to that for the dry season.

The wet season HYV rice output rose in all phases. However, the annual increase declined to 159,000 MT during 1989-1999 from 170,000 MT during 1968-1988. It accelerated to 316,000 MT during 2000-2009 with a further acceleration to 396,000 during 2010-2019. This notwithstanding, it appears that dry season HYV rice influenced the overall HYV rice output more than the wet season HYV rice output.

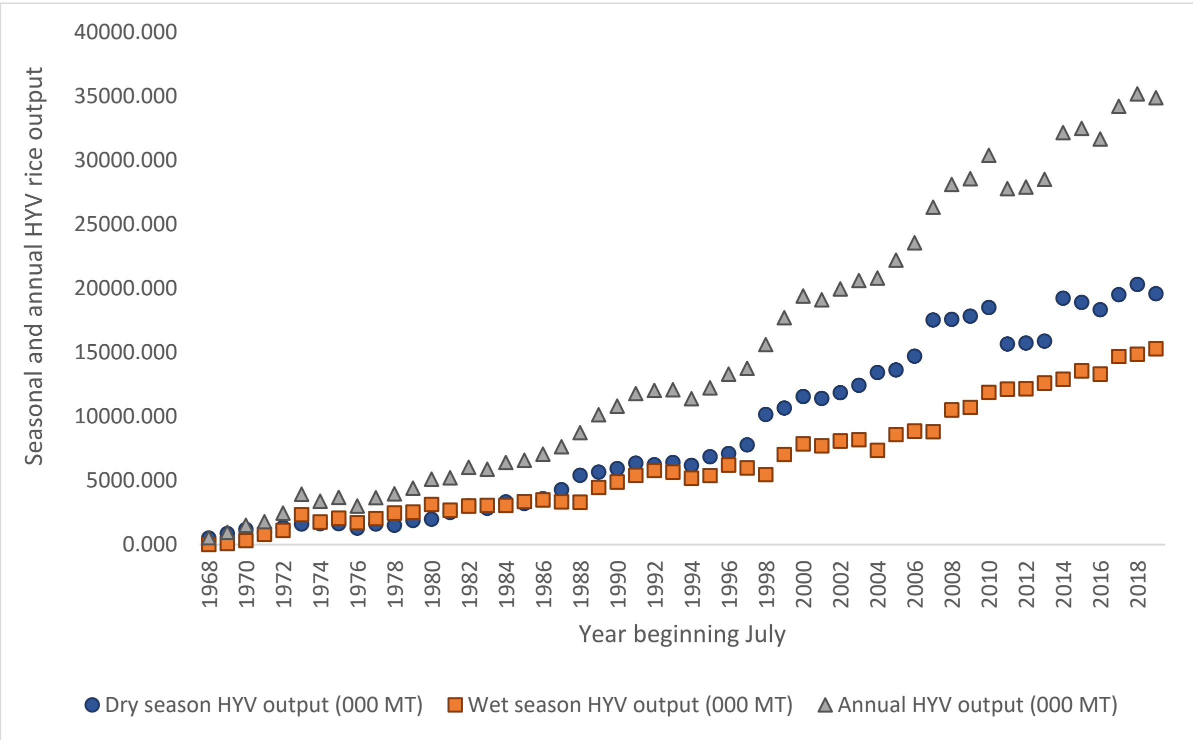

Figure 7: Trends in annual and seasonal outputs from HYV rice (000 MT) in various phases, Bangladesh 1968-2019.

Table 8: Trends in annual and seasonal outputs of HYV rice (000 MT) in different phases, Bangladesh 1968-2019

Annual HYV rice output (R^2 = 0.9952; F – statistic (7, 44) = 1604.10; N = 52)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy, $\hat{\alpha}_4$	Trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1968-1987	1988-1998	1999-2006	2007-2019	1968-1987	1988-1998	1999-2006	2007-2019
567.05^{b}	-1963.89	-5782.65^{c}	-1927.81	342.75^{a}	172.35^{b}	379.79^{a}	352.85^{a}
Estimated regression models for various phases (annual HYV rice output)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1987	1988-1998	1999-2006	2007-2019	1968-1987	1988-1998	1999-2006	2007-2019
567.05	-1396.83	-5215.59	-1360.75	342.71	515.05	722.50	695.55
Dry season HYV rice output (R^2 = 0.9903; F – statistic (7, 52) = 1376.30; N = 52)							
1968-1986	1987-1997	1998-2006	2007-2019	1968-1986	1987-1997	1998-2006	2007-2019
404.76^{a}	-632.89	-6805.73^{a}	7007.05^{b}	151.93^{a}	105.61^{b}	379.78	79.46^{a}
Estimated regression models for various phases (dry season HYV rice output)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1986	1987-1997	1998-2006	2007-2019	1968-1986	1987-1997	1998-2006	2007-2019
404.76	-228.13	-6400.97	7411.81	151.93	257.55	531.71	231.39
Wet season HYV rice output (R^2 = 0.9907; F – statistic (7, 44) = 1067.96; N = 52)							
1968-1988	1989-1999	2000-2009	2010-2009	1968-1988	1989-1999	2000-2009	2010-2019
312.82	998.48	-3481.60	-5763.95^{***}	169.69^{***}	-11.197^{***}	146.15^{***}	226.05^{***}
Estimated regression models for various phases (wet season HYV rice output)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1988	1989-1999	2000-2009	2010-2009	1968-1988	1989-1999	2000-2009	2010-2019
312.82	1311.32	-3168.78	-5451.13	169.69	158.50	315.84	395.75

$^{***}p < .01$; $^{**}p < .05$.

Table 9 presents the trends in annual and seasonal yields of HYV rice yield kg ha^{-1} in different phases during 1968-2019. The structural breaks are similar (Figure 8). Dry season HYV rice yield growth increased steadily from 21.5 to 26.8 kg ha^{-1} between 1968-1974 and 1975-1996 accelerating to 71 kg ha^{-1} during 1997-2006 before a slowdown to an annual increase of 28.7 kg ha^{-1} during 2007-2019.

The yearly change in annual HYV rice yield started with a decrease of ≈ 246 kg ha^{-1} during 1968-1974. Subsequent phases witnessed a turnaround and peaked with an annual increase of 42 kg ha^{-1} during 1998-2006. The 2007-2019 phase recorded a slowdown in the annual average increase to ≈ 25 kg ha^{-1}.

The wet season HYV rice yield after recording declines of ≈227 and 7 kg ha^{-1} respectively during 1968-1974 and 1975-1998, registered a small increase of ≈5 kg ha^{-1} during 1999-2009 before an accelerated increase of >30 kg ha^{-1} during 2010-2019.

Table 9: Trends in annual and seasonal yields of HYV rice per hectare cropped with rice (kg ha^{-1}) in different phases, Bangladesh 1968-2019

Annual HYV rice yield (R^2 = 0.9533; F – statistic (7, 44) = 417.80; N = 52)							
Intercept, $\hat{\alpha}_1$	Intercept dummy, $\hat{\alpha}_2$	Intercept dummy, $\hat{\alpha}_3$	Intercept dummy 3, $\hat{\alpha}_4$	Time trend, $\hat{\beta}_1$	Trend dummy, $\hat{\beta}_2$	Trend dummy, $\hat{\beta}_3$	Trend dummy, $\hat{\beta}_4$
1968-1974	1975-1997	1998-2006	2007-2019	1968-1974	1975-1997	1998-2006	2007-2019
3923.57***	-1681.28***	-2574.18***	-1803.24***	-245.79***	249.36***	287.82***	270.78***
Estimated regression models for various phases (annual HYV rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1974	1975-1997	1998-2006	2007-2019	1968-1974	1975-1997	1998-2006	2007-2019
3923.57	2242.29	1349.39	2120.33	-245.79	3.56	42.03	24.99
Dry season HYV rice yield (R^2 = 0.9759; F – statistic (7, 44) = 395.88; N = 52)							
1968-1974	1975-1996	1997-2006	2007-2019	1968-1974	1975-1996	1997-2006	2007-2019
857.56***	458.20***	-1596.23***	1158.48***	21.54***	5.25	49.27***	7.19
Estimated regression models for various phases (dry season HYV rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1974	1975-1996	1997-2006	2007-2019	1968-1974	1975-1996	1997-2006	2007-2019
857.56	1315.76	-738.67	2016.04	21.54	26.79	70.81	28.73
Wet season HYV rice yield (R^2 = 0.8514; F – statistic (7, 44) = 136.43; N = 52)							
1968-1974	1975-1998	1999-2009	2010-2019	1968-1974	1975-1998	1999-2009	2010-2019
3584.85***	-1402.46***	-1449.32***	-2352.95***	-226.88***	220.21***	232.01***	257.16***
Estimated regression models for various phases (wet season HYV rice yield)							
Intercept ($\hat{\alpha}_1 + \hat{\alpha}_i$), i = 2,., 4				**Trend ($\hat{\beta}_1 + \hat{\beta}_i$), i = 2,., 4**			
1968-1974	1975-1998	1999-2009	2010-2019	1968-1974	1975-1998	1999-2009	2010-2019
3584.85	2182.39	2135.53	1231.89	-226.88	-6.67	5.14	30.29

*** $p < .01$

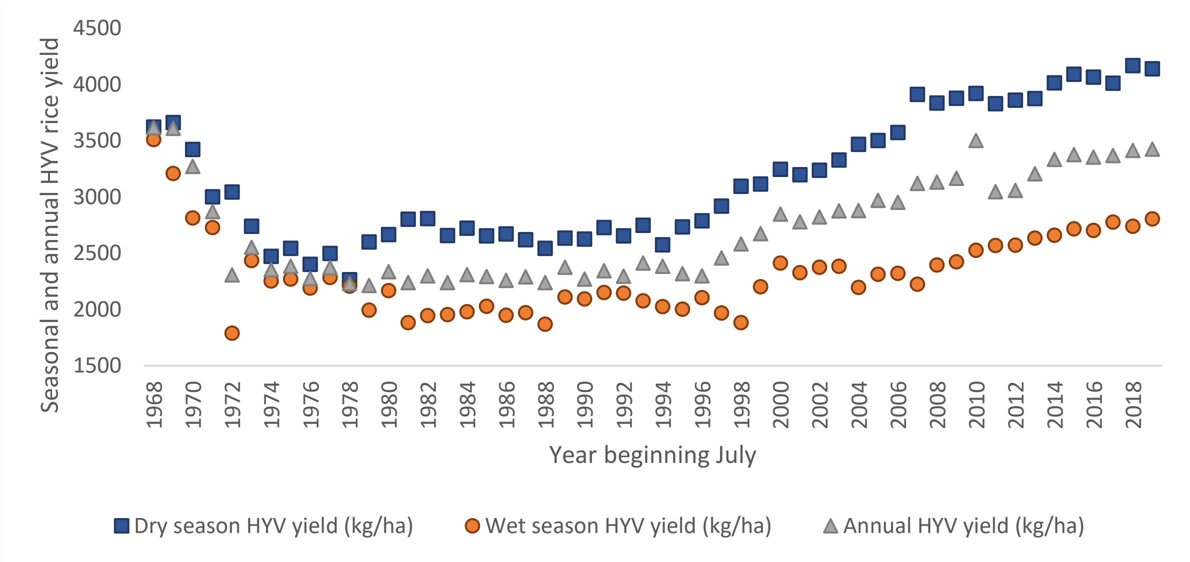

Figure 8: Trends in annual and seasonal yields of HYV rice (kg ha^{-1}) in various phases, Bangladesh 1968-2019.

6.3 A Resumé of Results

The results for the 1947-2019 period suggest that:

- The structural breaks differ between wet and dry seasons especially during initial phases. In most cases, the wet season turning points closely align with those for the annual picture.
- Dry season rice area, output and yield after growing steadily over the years, show signs of slowdown in the last decade or so. In contrast, the wet season rice output and yield have grown steadily, while its area has continued to fall after rising during the initial phase (1947-1970). However, the annual absolute decline in wet season rice area has flattened after peaking during 1988-2003.
- The slowdown in increase of annual rice yield and output is largely the outcome of the slowdown in the dry season output and yield despite being partially offset by increasing trends in their wet season counterparts.
- The increase in the percentage area under dry season rice and the associated spread of the HYV technology have underpinned trends in the annual rice yield.

We identify four phases during the 1968-2019 period. The first two phases clearly differ between seasons. Structural breaks tend to converge during the last two phases. The results suggest that:

- Two different time trajectories typify the diffusion of the dry and wet season HYV rice technology since the Green Revolution. In the wet season it was slow to start but was followed by a more rapid pace in contrast to its dry season counterpart.
- Trends in annual HYV rice area, output and yield and in those for the dry season demonstrate slowdowns in the recent decade or so. The wet season HYV rice area, output and yield, on the other hand, continue to grow steadily.

7. Discussion

Our results are consistent with those of Alauddin et al., (2021) in that the annual change in aggregate rice yield increase has experienced a significant slowdown in the last decade or so. Thus, the momentum of rice yield increase in the post-Green Revolution period has not been maintained. The results reveal that disaggregation by season provides greater insights into the production process and its time trajectories. We also found that structural breaks are not uniform across the board and caution against uniform cut-off points that could be somewhat arbitrary.

7.1 Observed trends in rice area, output and yields: Some plausible explanation

Rice production in Bangladesh takes place under a complex system of technological and eco-environmental conditions. These factors influence the levels and trends in output, yield and area under rice cultivation over time and across seasons over time.

Technological Influences

The Green Revolution in South Asia (including Bangladesh) and elsewhere has been critically dependent on the availability of irrigation facilities. Initial years witnessed the spread of HYVs of cereals limited to areas with pre-existing and well-developed irrigation facilities. Citing examples Mexico, Taiwan, the Indian Punjab and the South Indian state of Tamil Nadu Raj (1970, p.121) observed that "… When irrigation was extended to areas with good soil but where productivity of the land was relatively low earlier, owing to the inadequate supplies of water, such extension has led not only to an increase in the cropped area but to higher productivity all round".

The principal contribution of the Green Revolution in Bangladesh to higher crop productivity has resulted exclusively from increased productivity of already cultivated land and by multiple cropping underpinned by irrigation, not from an extension of area of cultivated land (Alauddin and Tisdell, 1986). A downward shift in the cost of internal land augmentation may arise due to the adoption of new technology and the complementarity between irrigation and the bio-chemical components (Alauddin and Quiggin, 2008, p.115). HYVs of rice were cultivated on >89% of all rice lands (>99% in the dry season, and ≈82% in the wet season) and contributed > 96% of the total rice output in 2019[8].

The spread of HYVs led to more than a tripling in overall rice yields and nearly a quadrupling of its output. The dry season rice crop has by far the highest yield due to far greater control over the production environment because of complete irrigation coverage and readier availability of and easier accessibility to complementary inputs than for the wet season. However, a significant increase in the area planted with HYV rice (in place of low yielding traditional rice varieties) during the wet season has also taken place at the same time. The combined effect of higher yield and a significant increase in the area planted with HYVs has brought to bear an increasing influence on the annual rice yield and output.

Eco-environmental influences

Over the last seven decades the crop (especially rice) production systems in Bangladesh have undergone profound changes manifesting in more intensive use of environmental capital (land and water). Furthermore, there has been a fundamental shift in the agro-ecosystem of rice production due to dependence on irrigation.

During 1947-1959 cropping intensity remained relatively stable hovering about 130%. This was driven by population pressure given the static nature of the agricultural technology (Boserup, 1965; 1981). A cultivation margin was extended to areas which were once left fallow or as culturable waste. The combination of these two declined from ≈ 2.8 m ha in the late 1940s to 1.3 m ha by the late 1950s and most recently (2015-2019) it declined even further to 0.65 m ha.

With the extensive margin almost exhausted, the only option left for Bangladesh was to intensify agriculture. Since the introduction of the non-biological components of the Green

[8] In 1997-1998 (three decades since the introduction of the Green Revolution) HYVs were cultivated on >51% of all rice lands (dry season >92%, wet season >37%) with a total rice output contribution of 61%.

Revolution technology (especially irrigation), cropping intensity steadily increased from just over 130% in 1960 to over 137% in 1966. With the introduction of HYVs in the late 1960s, cropping intensity gained further momentum reaching ≈ 160% by the mid-1980s. By 2019 it exceeded 197%. Since the Green Revolution fertilizer, irrigation and HYV inputs have played a critically important role in the intensification of Bangladesh (Binswanger et al., 1993).

Bangladesh has increasingly relied on irrigation, particularly from groundwater sources, to produce food grains to feed its growing population. In the early 1970s, >80% of the total irrigated area (just over 1 m ha) originated from surface water sources. Five decades later, 80% of the total irrigated area of 7.9 m ha (i.e., 6.3 m ha) utilized groundwater (BBS 2021, p.513) epitomizing a significant shift within the irrigated ecosystem.

8. Eco-Environmental Consequences

Two probable consequences might stem from the process of land use change over the last seven decades:

- reduced genetic diversity and ecological vulnerability.
- technological diffusion and associated environmental risks.

8.1 Genetic diversity and ecological vulnerability

Since the introduction HYVs of rice many traditional rice varieties were either on their way to extinction (not cultivated over a substantial area) or have become extinct (no longer planted with).[9]

While the Bangladesh national research system has developed over 100 rice varieties, they rest on a narrow genetic base (Kabir et al. 1994). An identification of the parentage reveals that a substantial chunk of the of prominent rice varieties indicate the narrowness of the genetic base of the new varieties (see BRRI, 2018, pp.7-8; Alauddin et al. 2021). According to Nouroallah (2016, p.53) "In Bangladesh, rice *in situ* diversity has undergone both absolute genetic erosion and change in the evenness of utilization of the existing diversity to the benefit of the MVs… However, an improved off-spring contains only a small share of the diversity of the parent

[9] Nouroallah (2016, p.52) reported 472 of the traditional *Aman* (late wet season) varieties and 426 of the local varieties of *Boro* (dry season) rice of case cases (see also Hossain et al., 2013).

landrace … each Bangladeshi landrace has a high level of genetic variation, whereas the MVs are monomorphic". Genetic uniformity reduces resistance or increases susceptibility to disease and insect attacks (Hardgrove et al., 1980). Substantially higher yields and shorter growing periods favored the cultivation of HYVs relative to local varieties but for local varieties with special characteristics.

An analysis of the adoption data of the prominent rice varieties (BRRI, 2018b, pp. 166-168) along with area and yield data from BBS (2019, p.39) suggest a high level of dependence on five strains of rice (BRRI *dhan*48, BRRI *dhan*28, BRRI *dhan*49m, BR 11, BRRI *dhan*28, and BRRI *dhan*29. This demonstratable level of dependence only on a limited number of rice strains exposes Bangladesh to a high ecological vulnerability.

8.2 Technological diffusion and associated environmental risks

Rapidly increasing groundwater dependency has led to a significant decline in water tables due to the withdrawal of water exceeding its recharge of aquifers in many areas of Bangladesh (BRRI, 2019; Alauddin et al, 2020). Parts of western, northwestern, and northern Bangladesh may be approaching physical water scarcity, due to a lack of sufficient water to meet all demands, including environmental flows (Alauddin and Sarker, 2014)[10]. In the drought-prone areas, the groundwater dependency far exceeds (≥ 95%; BBS, 2019) the national average for Bangladesh. Bangladesh's dependency on groundwater is one of the highest in the world and is consistent with the high overall groundwater dependency of the South Asian region (Alauddin and Quiggin, 2008; Shah, 2009). Furthermore, rice requires much more water than other crops such as wheat, vegetables, and fruits (Hasan et al., 2019). Furthermore, the cultivation of HYVs of rice creates significant environmental damage (Sabiha et al, 2016; Rahman 2010).

The use of agro-chemicals including chemical fertilizers rose dramatically over the last five decades. The application of chemical fertilizers rose from < 10 nutrient kg ha^{-1} in the late 1960s to nearly 300 kg more recently (Alauddin and Tisdell, 1991; http://www.fao.org/faostat/en/QC, accessed 18 April 2020).

The leaching of nitrates into groundwater from the use of chemical fertilizers in crop

[10] The World Bank (2013, p. 119) reported that on a scale of 0 to 1 (0 – no apparent threat, 1 – extremely threatened), Bangladesh's water security threat was extreme, varying between 0.8 and 1.

production adversely affects the water quality. Increased application of nitrogenous fertilizers to crops makes them more attractive to insect pests making crops more vulnerable to insect attacks (Mace and Mills, 2015; Marazzi et al, 2004; Yang et al, 2016).

It is widely recognized that the unintended consequences of water use, soil degradation, and chemical runoff have had serious environmental impacts beyond the areas cultivated (Pingali, 2012; Burney et al., 2010). Bangladesh has witnessed a sizeable increase in the application of pesticides over the last three decades. Its net application per net cropped ha. increased from 0.310 kg in 1990, dramatically to 3.378 kg in 2010 and then rose to 3.726 kg by 2019 (https://www.fao.org/faostat/en/#data/RP accessed 12 December 2021). Empirical evidence (e.g., Akter et al., 2018; Wilson and Tisdell, 2001) suggests a significant risk to human health from excessive use of agro-chemicals.

The success of Bangladesh in significantly augmenting its foodgrain (mostly rice) production has been critically dependent on the process of intensification. However, there are limits to which this process can be sustained indefinitely contrary to the optimism expressed by Ringler et al. (2014). Furthermore, the net area cultivated in Bangladesh is declining every year due to competing demand for land for industrialization, human settlement, urbanization and infrastructure development. There is ample evidence to suggest that land quality in 11 out of 32 agro-ecological zones in Bangladesh has been on the decline due to decrease in loss of soil fertility from intensive cultivation (Rahman, 2010). The cropping pattern embodying dry season rice, early wet season rice and late wet season rice has suffered the most from serious nutrient depletion (Rahman, 2010, p.265). Four more cropping patterns have experienced nutrient decline by more than 200 kg/ha/per year (Rahman, 2010, p.265). Rahman (2010, p. 266) also suggested that planting two crops annually and adding green manure significantly reduces the nutrient depletion rate.

9. Concluding Observations

Rice is the dominant crop grown in Bangladesh and constitutes a remarkably high proportion of the diet of Bangladeshis, especially of those who are on lower incomes. Maintaining adequate supplies of rice has, therefore, been high on the agenda of the governments of Bangladesh. This article has traced out how Bangladesh has succeeded in increasing its rice supplies during the seven decades (1947-2019). This has principally been made possible by the diffusion of HYVs of rice, mainly in the dry season, and in more recent times, in the wet season.

In the latter season, this diffusion has lagged in the dry season. The main contribution to increased rice production in Bangladesh has been its production in the dry season but nevertheless somewhat more rice is produced in the wet season than before.

Our detailed results confirm that, as far as trends in Bangladeshi rice production are concerned:

- Structural breaks differ between dry and wet seasons for the same variable or among different variables.
- Annual and seasonal outputs, areas and yields of overall HYV rice exhibit a slowdown in their increase in the last decade or so. The source of this slowdown arises mainly from changes in these variables in the dry season.
- The diffusion of the HYV rice technology exhibits differential patterns between seasons. During the dry season HYVs spread at a much faster rate than for the wet season due to the readier and assured availability of irrigation and other complementary inputs. On the other hand, the wet season adoption of HYVs started slowly due to a lower degree of their adaptability to the rainfed ecosystem.
- The increasing percentage area under the dry season rice crop has significantly underpinned increased annual rice yield.
- The growth in outputs and yields of HYV rice exhibit significant differential patterns by dry and wet seasons. The dry season yields are appreciably higher than those for the wet season. However, a slowdown in the dry season rice HYV output and yield is in evidence in the last decade or so.

It is clear from this analysis that prior to the Green Revolution, Bangladesh faced the unsavory prospect of increasing poverty due to population growth outpacing its ability to increase production of rice. However, following the Green Revolution, Bangladesh has been able to substantially increase its level of population, has achieved a higher per capita level of income than previously, and has reduced its incidence of poverty. Nevertheless, Bangladesh’s scope for further raising rice production appears to be limited as has been demonstrated in this article. Bangladesh might, in the future, experience an increase in the incidence of poverty due to the inability of its output of rice to keep pace with its population growth. This possibility cannot be dismissed as pointed out in this paper (see Alauddin et al., 2021).

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Appendix Table 1: Rice crop calendar, ecosystem, and broad crop season in Bangladesh and variable description

Rice crop	Ecosystem	Broad crop season	Sowing/ transplanting period	Harvest period
Aus – local broadcast	Rainfed	Wet	Mid-March to mid-April	Mid-July to early August
Aus – HYV transplant	Rainfed with supplementary irrigation	Wet	Mid-March to mid-April	July to August
Aus – HYV broadcast	Rainfed with supplementary irrigation	Wet	Mid-March to mid-April	Late July to August
Aman – local transplant	Rainfed	Wet	End June to early September	December to early January
Aman – local broadcast	Rainfed	Wet	Mid-March to mid-April	Mid-November to mid-December
Aman – HYV transplant	Rainfed with supplementary irrigation	Wet	Late June to mid-August	December to early January
Boro - local	Irrigated	Dry	Mid-November to mid-January	April to May
Boro - HYV	Irrigated	Dry	December to mid-February	Mid-April to June
Boro - hybrid	Irrigated	Dry	December to mid-February	Mid-April to June

Variable	Description
Wet season rice	*Aus* + *Aman* rice crops = *Aus* local + *Aus* HYV (broadcast and transplant) + *Aman* local (transplant and broadcast) + *Aman* HYV
Wet season HYV rice	*Aus* HYV (broadcast and transplant) + *Aman* HYV
Dry season rice	*Boro* local + *Boro* HYV + *Boro* hybrid
Wet season HYV rice	*Boro* HYV + *Boro* hybrid
Annual rice area (000 ha)	Wet season rice area + Dry season rice area
Annual rice output (000 MT of cleaned rice = $\frac{2}{3}\ x$ paddy)	Wet season rice output + Dry season rice output
Annual rice yield (kg ha^{-1})	(Annual rice output) ÷ (Annual rice area) x 1000
Wet season rice yield (kg ha^{-1})	(Wet season rice output ÷ Wet season rice area) x 1000
Dry season rice yield (kg ha^{-1})	(Dry season rice output ÷ Dry season rice area) x 1000
Wet season HYV rice yield (kg ha^{-1})	(Wet season HYV rice output ÷ Wet season HYV rice area) x 1000
Dry season HYV rice yield (kg ha^{-1})	(Dry season HYV rice output ÷ Dry season HYV rice area) x 1000
Area single cropped	Area cropped once during a calendar year
Area double cropped	Area cropped twice during a calendar year
Area triple cropped	Area cropped three times during a calendar year
Area quadruple cropped	Area cropped four times during a calendar year
Gross cropped area	Single cropped area + 2 x Double cropped area + 3 x Triple cropped area + 4 x quadruple cropped area
Net cropped area	Single cropped area + Double cropped area + Triple cropped area + Quadruple cropped area
Cropping intensity	(GCA ÷ NCA) x 100

Source: Adapted from BBS (2020a).

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