ISSN 1327-8231

ECONOMICS, ECOLOGY AND THE ENVIRONMENT

Working Paper No. 210

Have Conway's Predictions about the Effects of the Green Revolution been Realized? An Investigation of Six Decades of Bangladeshi Rice Data

by

Mohammad Alauddin

Clement A. Tisdell

Md. Abdur Rashid Sarkar

January 2021

THE UNIVERSITY OF QUEENSLAND

ISSN 1327-8231

WORKING PAPERS ON

ECONOMICS, ECOLOGY AND THE ENVIRONMENT

Working Paper No. 210

Have Conway's Predictions about the Effects of the Green Revolution been Realized? An Investigation of Six Decades of Bangladeshi Rice Data[1]

by

Mohammad Alauddin[2]

Clement A. Tisdell[3]

Md. Abdur Rashid Sarkar[4]

January 2021

[1] A draft of a paper to be submitted as a journal article.

[2] School of Economics, The University of Queensland, St Lucia Campus, Brisbane, QLD, 4072, Australia Email: m.alauddin@uq.edu.au

[3] School of Economics, The University of Queensland, St. Lucia Campus, Brisbane QLD 4072, Australia Email: c.tisdell@uq.edu.au

[4] Department of Economics, University of Rajshahi, Rajshahi, Bangladesh 6205 (rashid_econ@ru.ac.bd)

The *Economics, Environment and Ecology* set of working papers addresses issues involving environmental and ecological economics. It was preceded by a similar set of papers on *Biodiversity Conservation* and for a time, there was also a parallel series on *Animal Health Economics*, both of which were related to projects funded by ACIAR, the Australian Centre for International Agricultural Research. Working papers in *Economics, Environment and Ecology* are produced in the School of Economics at The University of Queensland and since 2011, have become associated with the Risk and Sustainable Management Group in this school.

Production of the *Economics Ecology and Environment* series and two additional sets were initiated by Professor Clem Tisdell. The other two sets are *Economic Theory, Applications and Issues* and *Social Economics, Policy and Development*. A full list of all papers in each set can be accessed at the following website: http://www.uq.edu.au/economics/PDF/staff/Clem_Tisdell_WorkingPapers.pdf

For further information about the above, contact Clem Tisdell, Email: c.tisdell@uq.edu.au

In addition, the following working papers are produced with the Risk and Sustainable Management Group and are available at the website indicated. *Murray-Darling Basin Program, Risk and Uncertainty Program, Australian Public Policy Program, Climate Change Program* :http://www.uq.edu.au/rsmg/working-papers-rsmg

For further information about these papers, contact Professor John Quiggin, Email: j.quiggin@uq.edu.au

Have Conway's Predictions about the Effects of the Green Revolution been Realized? An Investigation of Six Decades of Bangladeshi Rice Data

Abstract

This is the first empirical evaluation of Conway's pioneering predictions about the effects of the Green Revolution on crop yield levels, their sustainability and variability in a long-term context using a holistic approach involving economic, environmental, and ecological factors. It analyses trends in Bangladeshi rice production and identifies changing relative contributions to variations in aggregate rice output of alterations in aggregate rice yields and in the rice area cropped. Rice yields rose substantially following the Green Revolution and have been the major contributor to increasing rice output but have become almost stationary recently. This stationarity (if sustained) could result in Bangladesh finding it increasingly difficult to feed its growing population. Because of the high dependency of Bangladesh on just a few HYVs of rice (and its shrinking gene pool) the productivity of its rice crop could be vulnerable to major ecological and environmental shocks. We found that until recently, the absolute variability of rice yields was higher after the early establishment of the Green Revolution than prior to it. The relative variations in rice yields away from their trend values were smaller after the Green Revolution was well established and continued to fall with the widespread adoption of the technologies. We highlighted the trio of general factors determining rice yields. Holistic analysis requires these all to be considered. However, non-economists often overlook economic factors explored here in assessing influences on the crop yield levels while economists often do not pay adequate attention to ecological and environmental factors. Furthermore, this study contributes to the land-saving controversy involving the intensification of agriculture. The analytical framework we have employed can be adapted to other countries with similar biophysical and demographic characteristics.

Keywords: Bangladesh, Green Revolution, Food security, Properties of agroecosystems, Agricultural intensification; Rice sustainability, Rice yields.

JEL classification: O1; Q0; Q2

HIGHLIGHTS

- First holistic study on Conway's prognosis about Green Revolution on level, variability, and sustainability of crop yields
- Significant rice yield increase after Green Revolution, near stationary more recently in Bangladesh
- Assesses ecological, environmental, and economic impact on rice yield sustainability in Bangladesh
- Little evidence of land-saving following agricultural intensification in Bangladesh
- Analytical framework employed adaptable to other contexts with similar biophysical and demographic characteristics

Have Conway's Predictions about the Effects of the Green Revolution been Realized? An Investigation of Six Decades of Bangladeshi Rice Data

1. Introduction and Background

Gordon Conway (Conway, 1985; 1987) made some pioneering predictions about the possible outcomes of the Green Revolution technologies introduced in many countries including those in South Asia in the late 1960s and the early 1970s. The basic hypotheses of Conway can be encapsulated as follows: In comparison to traditional agroecosystems,

1. Yields and incomes from Green Revolution crops are higher, but
2. They are less sustainable.
3. The variability of yields may be higher or lower but are likely to be higher in the early stages of the adoption of Green Revolution agroecosystems.
4. Income is likely to be more unequally distributed – the distributional outcome is less equitable.

Note that there are similarities between Conway's analysis and Barbier's three-pillar sustainability concept (economic, environmental, and social) (Barbier, 1987). Conway's analysis suggests that the Green Revolution could threaten ecological, economic, and social sustainability.

Using 60 years of data on Bangladesh's rice production this paper explores whether it supports the first three hypotheses of Conway[1]. More specifically, the main purpose of this article is to investigate the extent to which the hypotheses of Conway about level, sustainability, and variability of yields have been realized. The issues raised by Conway over 30 years ago are of considerable significance to developing countries including Bangladesh, which is now highly dependent on Green Revolution agriculture for its food security. Bangladesh depends heavily on its rice production for most of its food requirements, predominantly using Green Revolution technologies.

Globally, Bangladesh is the fourth largest producer of rice with an average annual production of 34 m MT over the five-year period 2015-2019. China (148 m MT), India (111 m MT) and Indonesia (37 m MT) were the three countries with higher levels of annual rice output for the corresponding period (https://www.indexmundi.com/commodities/?commodity=rice&months=60 (accessed 2

December 2019). As of 2017, Bangladesh had by far the highest percentage of gross cropped area allocated to rice on its arable land (146.4%) followed by Vietnam (110.3%), and the Philippines (86.1%). Interestingly enough, for the two most dominant rice-producing countries, China and India, the corresponding values were 25.7% and 28.0% respectively (http://www.fao.org/faostat/en/#data/QC, accessed 5 February 2020).

The per capita annual consumption of rice in Bangladesh in 2016 was 134 kg. compared to 152 kg. in 2010[2]. This decline notwithstanding, Bangladesh's rice consumption per capita remains far higher than that of its South Asian neighbours, more than double that of India, and about 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 still by far the major component of this diet (BBS, 2017). Although Bangladesh's population growth rate has declined significantly, the level of population is still rising and likely to reach 216.46 million in 2051 and 223.390 million in 2061 (BBS, 2015, pp.34-35). Given Bangladesh's 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 increase in Bangladesh's population (Islam and Talukder, 2017; BPC, 2018).

This paper proceeds as follows. Section 2 presents materials and methods. A presentation of the results follows in Section 3. Section 4 explores factors, which threaten the long-term future sustainability of Bangladesh's rice yields and the level of its rice production. Section 5 investigates the extent to which the hypotheses of Conway about the level of yields and their sustainability have been satisfied. Following up another hypothesis of Conway, we also investigate whether and why yields have experienced increased or decreased variability in Bangladesh as HYVs of rice have been more widely adopted. Section 6 provides conclusions.

This research contributes to the existing literature in several important ways. It is the first long-term empirical investigation of the impact of the Green Revolution on the level of rice output and the size of yield, and the variability of these. Secondly, it provides an empirical assessment of the pioneering predictions of Gordon Conway about the effects of the Green Revolution on the nature of crop yields in a long-run context. Furthermore, it contributes to the land-saving controversy involving the intensification of agriculture. Overall, our study adopts a holistic approach by combining agro-ecological and economic approaches to examine the sustainability of rice production.

2. Materials and Methods

2.1 The Data

The basic data of rice output, area and yield for Bangladesh 1960-2019 came from (https://www.indexmundi.com/commodities/?commodity=rice&months=60 (accessed 2 December 2019). Output refers to m MT of annual milled rice. The corresponding area and yield are measured in m ha and kg ha^{-1}. These data form the primary empirical basis of our investigation.

The analysis and discussion of results, and matters relating to seasonal rice yields, irrigation, genetic diversity, and application of agro-chemical inputs in Section 4 and Section 6 required supplementary information from a range of sources including:

- Various issues of the *Yearbook of Agricultural Statistics* published annually by the Bangladesh Bureau of Statistics.
- *Annual Reports* of the Bangladesh Rice Research Institute.
- The Food and Agriculture Organization database.
- Relevant published materials for specific information where appropriate.

2.2 Analytical Frameworks

This study employed three analytical frameworks: (a) regression analysis involving dummy variables and the robust standard error model to estimate trends in output, yield and area under the cultivation of rice; (b) decomposition of the sources of growth in annual rice output; and (c) multiple measures of variability in rice output and yield.

2.2.1 Regression model specification for determining trends in rice output, yield and area planted

We define a regression model for the time series data for the annual rice output, yield and area. It is reasonable to assume that over the sixty-year period, technological change amongst others, has influenced the time path of the relevant variables. Bangladesh introduced the Green Revolution in phases. It commenced with the distribution of modern irrigation technologies like shallow, deep tube-wells (STWs and DTWs) and low lift pumps (LLPs) and chemical fertilizers in the early 1960s. It was only in the late 1960s and early 1970s with the introduction of the high yielding varieties (HYVs, or also known as modern varieties, MVs) that the Green Revolution assumed any significance (Alauddin and Tisdell, 1991).

A priori, rice output, yield and area could exhibit different growth trajectories during the sixty-year period. For example, there might be a phase in which output might grow more rapidly than in some others. In some phases, a slowdown might occur. Consequently, the regression lines for each phase might differ both in slope and in intercept making them dissimilar regressions (Gujarati, 2003). This may be due to the pace of technology diffusion and scientific breakthroughs that lead to an outward shift in the production function.

To incorporate the above, we postulate the following regression model:

Rice output (P), yield (Y) or area (X) = $\alpha_1 + \alpha_i D_{ti} + \beta_1$ Time + $\beta_i D_{ti}$ Time + u_t (1)

Where $i = 2 \ldots$n, n identifies the number of phases in a time series

α_1 = intercept for the reference period

β_1 = slope of the trend line for the reference period

α_i = intercept of the i th phase

β_i = slope of the trend line of the i th phase

D_{ti} = dummy variable, 1 for observations in Phase i and 0 for observations for other phases.

u_t = error term

Time = 1, 2,…, 60 for 1960, 1961, ..., 2019.

Thus, the estimated functions for various phases can be stated as follows:

Phase 1: Output/Yield/Area = $\hat{\alpha}_1 + \hat{\beta}_1$ Time (2)

Phase i: Output/Yield/Area = $(\hat{\alpha}_1 + \hat{\alpha}_i) + (\hat{\beta}_1 + \hat{\beta}_i)$ Time (3)

The efficiency of an ordinary least squares (OLS) estimator critically depends, among other things, on the validity of the following two assumptions about the error term:

1. $E(u_i^2) = \sigma^2$, $i = 1, \ldots$ n i.e., the errors have a constant variance or are homoscedastic (Gujarati, 2003, p.387); and
2. $E(u_i u_j) = 0$, $i \neq j$ i.e., the error term relating to any observation is independent of that for any other observation (Gujarati, 2003, p.442).

The violation of these two assumptions causes the OLS standard errors and statistics to be misleading as they typically underestimate the true uncertainty in the parameters (Wooldridge, 2020, pp.419-420). This calls for computation of standard errors and test statistics that are robust to general serial correlation and heteroscedasticity. Thus, both in theory and in empirical analysis, it is very common to use OLS and compute the so-called heteroscedasticity and autocorrelation consistent (HAC) standard errors to obtain unbiased and consistent OLS estimators.

2.2.2 Decomposition of the sources of growth in rice output

We now examine the sources of change in rice output using the decomposition technique specified in Equations (4-6) (adapted from Tisdell et al., 2019, p.13)[3].

$$P_2 - P_1 = (X_2 - X_1)\, Y_1 + (Y_2 - Y_1)\,(X_2 - X_1) \tag{4}$$

Where

$P_2 - P_1$ = output change between period 1 and period 2,

$X_2 - X_1$ = change in cropped area between period 1 and period 2,

$Y_2 - Y_1$ = yield change between period 1 and period 2.

The first term on the RHS of Equation (4) represents the absolute change in output due to the changed area of the crop given the yield in Period 1. The second term represents the absolute change in output resulting from the altered yield, considering the change in the area planted.

Given this type of decomposition, Equation (5) and Equation (6) respectively represent the percentage of the change in output due to the variation in area planted with the crop and the changed output attributable to changes in its yield. Thus:

$$\text{Area effect (\%)} = [(X_2 - X_1)\, Y_1 \div (P_2 - P_1)] \times 100 \tag{5}$$

$$\text{Yield effect (\%)} = [(Y_2 - Y_1)\,(X_2 - X_1) \div (P_2 - P_1)] \times 100 \tag{6}$$

The area and yield effects add up to 100%.

2.2.3 Measures used for determining trends in the variability in rice output and yield

Conway was unsure how the adoption of Green Revolution cropping would alter the variability of yields. We, therefore, decided to examine the variability pattern, which has emerged for rice in Bangladesh using four measures:

(1) absolute values of (i) all deviations about the trend and (ii) only those deviations below the trend, and

(2) the relative sizes of (iii) all deviations about the trend; and (iv) the deviations below the trend.

Our primary interest, however, lies in the absolute deviations below the trend not those above. This is consistent with an individual decision maker's perspective that when output and yield (by implication farm income) fall below the trend it tends to reduce utility by more than the gain in utility from a similar deviation above the trend given the law of diminishing marginal utility.

3. Results

3.1 Scatter Plots and Identification of Phases

Figures 1, 2 and 3 present the scatter plots for rice output, yield, and area under cultivation for the 1960-2019 period. The time trajectories of rice output, yield, and area under cultivation indicate four different phases within the sixty-year period. The intercepts and slopes for all three variables differ in each of these phases.

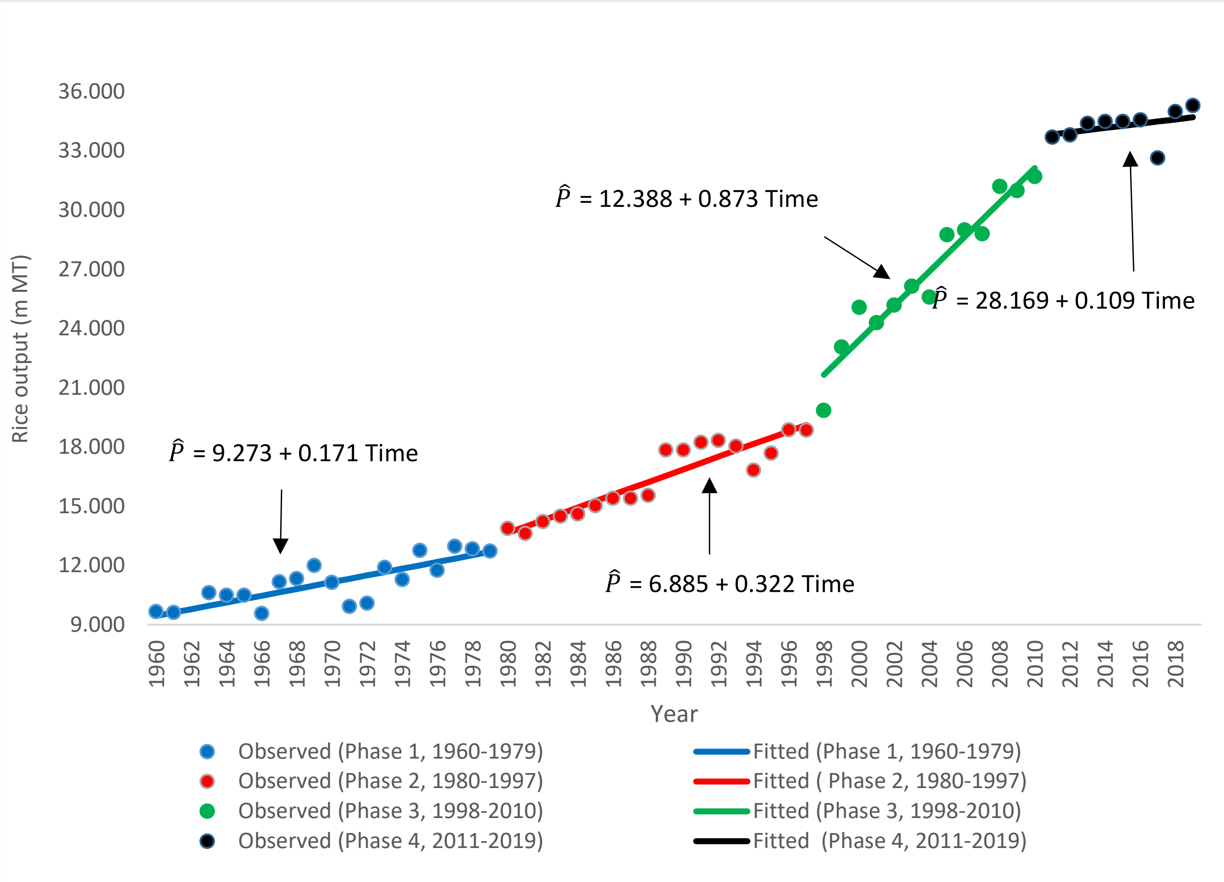

Figure 1: Changing trends in annual rice output, *P* (m MT) in various phases, Bangladesh 1960 – 2019 (Source: Based on Table 1, Column 3).

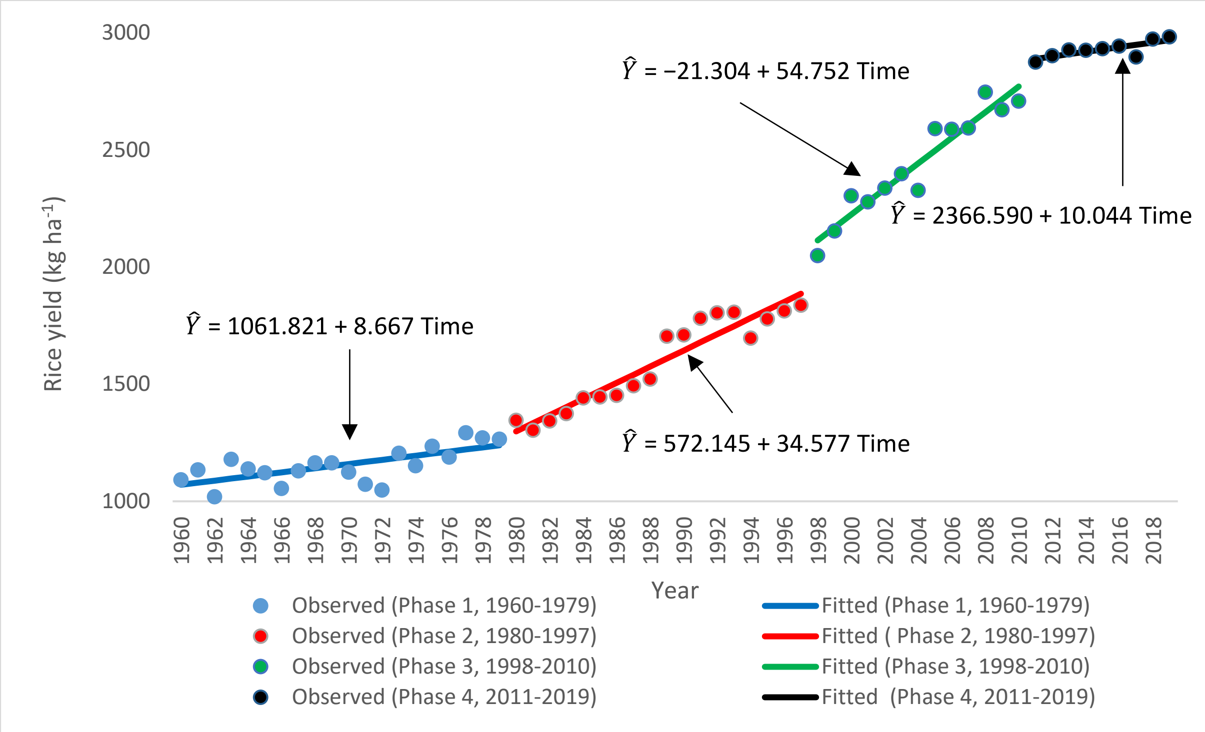

Figure 2: Changing trends in annual rice yield Y (kg ha^{-1}) in various phases, Bangladesh 1960 – 2019 (Source: Based on Table 1, Column 4).

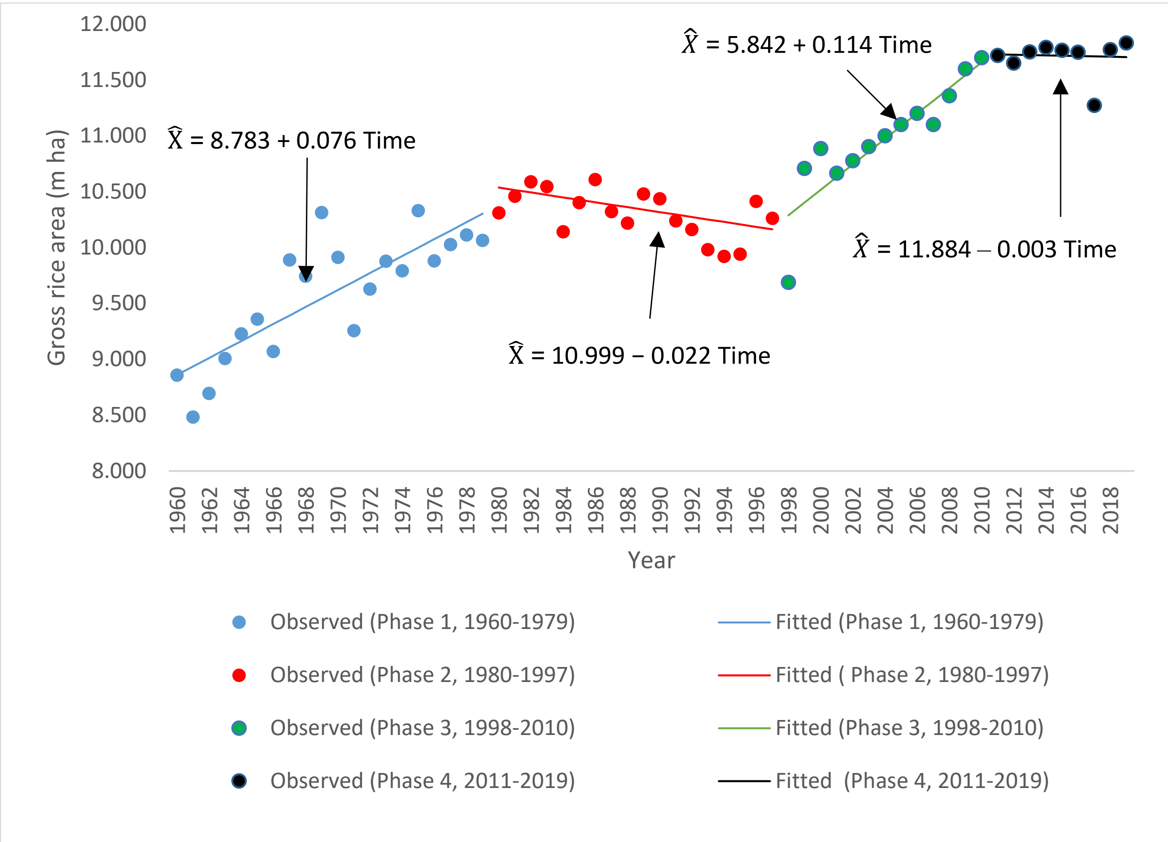

Figure 3: Changing trends in annual gross rice area X (m ha) in various phases, Bangladesh 1960 – 2019 (Source: Based on Table 1, Column 5).

Phase 1 (1960-1979): The Pre- and early Green Revolution phase (reference period). The decade of the 1960s marked in the main the pre-Green Revolution period even though the late 1960s heralded its beginning. Nevertheless, the effect of Green Revolution technologies upon yield and output was not manifestly clear until a decade or so later. Therefore, we can regard the first two decades (1960-1979) as the reference period.

Phase 2 (1980-1997): The initial establishment phase of the Green Revolution (first structural break). The Green Revolution technology firmly established itself by the late 1990s, due largely to the rapid expansion of dry season irrigation. This extended the cultivation of HYVs of rice in the dry season. The scatter plots in Figures 1 and 2 indicate that during this period there was an upward trend of movement in rice output and yield relative to their levels in the 1960-1979 period. At the same time, the gross area under rice cultivation registered a declining trend in this phase in contrast to that in the 1960-1979 period (Figure 3). Therefore, we consider the 1980-1997 period to represent the **first structural break**.

Phase 3 (1998-2010): The Mature Green Revolution phase (second structural break): This period is typified by a significant expansion of the absolute area of land under dry season cultivation of (*Boro*) rice. It rose from 3.281 m ha in 1998 to > 4.720 m ha in 2010, an increase of 43.9%. Almost all the *Boro* rice crop came under HYVs. While there was a net decline in rice area in the early monsoon (*Aus*) season, an increasing proportion of the remaining land consisted of HYVs. The total area planted with rice in the wet season (the Aman crop) was appreciably lower than for 1960-1980. The adoption rate of Aman HYVs of rice lagged far behind the adoption rate of the other two seasonal rice crops (http://brri.gov.bd). Overall, the area planted with rice witnessed a significant increase in this period. The scatter plots illustrated in Figures 1, 2, and 3 indicate that this period exhibited an upward trend in rice output, yield, and area under cultivation relative to those in the 1960-1979 period. Therefore, the 1998-2010 period, which was characterized by a much higher growth path for rice output, yield and area than the previous period, represents the **second structural break.**

Phase 4 (2011-2019): The Slowdown phase (third structural break): The last nine years (2011-2019) of the time series shows a slowdown in the growth rate of rice output, yield and area under cultivation. Therefore, it represents the **third structural break.**

3.2 Regression Results

We now explore the direction and magnitude of trends in rice output (*P*), yield (*Y*) and area under cultivation (*X*) by applying the robust standard error regression method to the time series data for the 1960-2019 period stated in Section 3.2. Because of the apparent differences in the intercepts and slopes between phases we require three dummy variables. This is consistent with the regression model specified in Equation 1.

Table 1 presents the estimated regression results. The estimated equations for all the three variables with very high explanatory powers ($\bar{R}^2$ > 0.99) and the F-statistic, demonstrate the overall quality of the estimates. The information contained in Table 1 embodies the following salient features of the regression results:

- The intercept dummies for 1980-1997, 1998-2010 and 2011-2019 differ significantly from those for the 1960-1979 period for all three dependent variables (output, yield and area). Overall, the estimated regression model demonstrates significant positive time trends in the three variables (row 5, columns 3-5, Table 1). Both output and yield have experienced significantly higher absolute increases in Phase 2 and Phase 3 compared to those during 1960-1979. However, the slope dummies for both output and yield (row 8, columns 3 and 4) in Phase 4 lack statistical significance indicating that they did not grow by amounts significantly different from their respective 1960-1979 (fitted) values. In Phase 4, output shows a non-significant but negative trend while yield shows a non-significant but weaker positive trend relative to 1960-1979. The time trajectory of the rice area planted displays a different pattern. Compared to its 1960-1979 level, estimated annual change in the area planted declined in Phase 2, increased in Phase 3 but declined again in Phase 4.

- **Rice output** increased by an estimated constant amount of about 171,000 MT annually during 1960-1979 (row 5, column 3). It rose by 322,000 MT annually [=171,000 (row 5) + 151,000 (row 6) of column 3] during 1980-1997 (that is by over 1.88 times its yearly increase during 1960-1979). In Phase 3, 1998-2010, it was estimated to have grown by 873,000 MT [=171, 000 (row 5) + 702,000 (row 7) of column 2] annually (that is by more than five times its annual absolute growth for 1960-1979). In Phase 4, output changed annually by an estimated amount of 109,200 MT [=171, 000 (row 5) - 61,800 (row 8) of column 2] which as indicated by the *p*-value (row 8, column 2) is not statistically significantly different from that for the 1960-1979 period.

- **Rice yield** increased annually by 8.67 kg ha^{-1} (row 5 of column 4) during Phase 1, 34.58 kg ha^{-1} [= 8.67 (row 5, col.4) +25.91 (row 6, col. 4), ≈ four times the fitted Phase 1 value] and 54.75 kg ha^{-1} [= 8.67 (row 5, col. 4) +46.08 (row 7, col. 4), 6.3 times the fitted Phase 1 amount] during Phase 3. The estimated annual yield change in Phase 4 was 10.05 kg. not statistically significantly different from the 1960-1979 level as indicated by the *p*-value (row 8, col. 4).

- **The gross area** cropped with rice was estimated to rise by 75,600 ha year^{-1} (row 5, col. 5) during 1960-1979. (Phase 1), fell by 21,800 ha year^{-1} (=75,600 – 97,400, rows 5+6, col.) and by 3,300 year^{-1} (=75,600 – 78,900, rows 5+7, col.) annually during Phase 2 and Phase 4 respectively relative to the one for Phase 1. The slope dummy for Phase 3 while positive, lacked statistical significance. This indicates that the annual change in area under rice cultivation in Phase 3 was not statistically significantly different from that in for Phase 1.

Table 1: Trends in annual rice output (m MT), yield (kg ha^{-1}) and gross cropped area (m ha), Bangladesh, 1960-2019 (based on robust standard error regression).

Row #	Coefficient	Estimated regression models for		
		Output ($\hat{P}$)	Yield ($\hat{Y}$)	Area ($\hat{X}$)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5
1	Intercept	9.2737 (.001)***	1061.821 (.001)***	8.7832(.001)***
2	Intercept dummy 1 (1980-1997 = 1, 0 else)	-2.3881 (.001)***	-489.6764 (.001)***	2.1610 (.001)***
3	Intercept dummy 2 (1998-2010 = 1, 0 else)else)	-21.6611 (.001)***	-1083.125 (.001)***	-2.9410 (0.018)**
4	Intercept dummy 3 (2011-2019 = 1, 0 else)	18.8961 (.001)***	1304.761 (.001)***	3.1011 (.004)***
5	Time trend (=1 for 1960 … 60 for 2019)	.17078 (.001)***	8.6671 (.001)***	.0756 (.001)***
6	Slope dummy 1 (1980-1997 = 1, 0 else)	.15115(.0001)***	25.9102 (.001)***	-.0974 (.001)***
7	Slope dummy 2 (1998-2010 = 1, 0 else)	.70232 (.001)***	46.0847 (.001)***	.0385 (.159)
8	Slope dummy 3 (2011-2019 = 1, 0 else)	-.06181 (.775)	1.3766 (.679)	-.0789 (.001)***
10	$\bar{R}^2$	0.9918	0.9923	0.9238
11	*F*- statistic (7,52)	2507.28***	3132.61***	179.63***
12	*N*	60	60	60

Note: *** *p* < .01, ** *p* < .05. Figures in parentheses in columns 3-5 represent *p*-values. Source: Based on data from https://www.indexmundi.com/commodities/?commodity=rice&months=60 (accessed 2 December 2019).

Figures 1, 2 and 3 illustrate the trend lines (columns 3-5, Table 1) for rice output, yield and area respectively and make it easy to compare the trajectories of these three variables in their various phases as stated above.

It is clear from Figure 2, that in accordance with Conway's first hypothesis, rice yields are much higher after the Green Revolution than before. They are in fact nearly three times as high typifying a remarkable increase in yields. As for his second hypothesis, this has not yet been satisfied. So far, higher rice yields have been sustained but their rate of increase has slowed considerably in recent years (Phase 4) and this rate of increase is barely higher than in Phase 1. The momentum growth of rice yields following the Green Revolution has not been maintained.

3.3 Results from the Decomposition Analysis

It is also relevant to consider the comparative importance of increases in the area planted with rice and the yield of rice as contributors to the total level of rice production in Bangladesh. The first component relates to the extension of rice production and the second is a result of its intensification of cultivation.

Employing the formulae specified in Equations (5-6), this section investigates the sources of fitted output changes between the first and final years of each phase attributable to changes in corresponding yield and area under cultivation. We also examine the contributions of alterations in yield and area at the two extremities of the entire time series. Extremity 1 and Extremity 2 refer respectively to the five-year averages of observed values of output, yield, and area of rice for 1960-1964 and 2015-2019. We have used the five-year average of observed values instead of the single-year figures to moderate the effect of any annual fluctuations. The analysis is based on fitted values, in contrast to the one based on observed values in order to embody a stochastic relationship and hence, randomness.

Panel A of Table 2 presents changes in the fitted values of rice output, yield and area for the first and final years of each phase while Panel B presents the five-year average of observed values for all the three variables between Extremity 1 and Extremity 2. Thus, the information presented in columns 2-10 of Table 2 forms the empirical basis for analyses of fitted and observed values of rice output, area and yield.

Table 2: Percentage contributions of area and yield in rice output change between fitted values in the first and last years of the four time phases, and between the averages of the observed values of the first (1960-1964) and the last five years (2015-2019), Bangladesh, 1960-2019.

Phase	**Panel A: Based on fitted values at two extremities within a phase**										
	Fitted output value ($\widehat{P}$)(m MT) in year of phase			**Fitted yield value ($\widehat{Y}$)(kg ha^{-1}) in year of phase**			**Fitted area value ($\widehat{X}$)(m ha) in year of phase**			**Percentage change in output due to**	
	First	Last	$\widehat{\Delta P}$	First	Last	$\widehat{\Delta Y}$	First	Last	$\widehat{\Delta X}$	Yield effect	Area effect
	Col. 2	***Col. 3***	***Col. 4***	***Col. 5***	***Col. 6***	***Col. 7***	***Col. 8***	***Col. 9***	***Col. 10***	***Col. 11***	***Col. 12***
Phase 1 (1960-1979)	9.443	12.688	3.245	1070	1235	165	8.807	10.243	1.436	52.3	47.7
Phase 2 (1980-1997)	13.645	19.118	5.473	1298	1886	588	10.542	10.171	-0.370	108.7	-8.7
Phase 3 (1998-2010)	19.118	32.140	10.477	1886	2771	657	10.171	11.661	1.369	72.6	27.4
Phase 4 (2011-2019)	33.835	34.707	0.872	2889	2969	80	11.913	11.886	-0.026	108.7	-8.7
1960-1964 (Extremity 1) and 2015-2019 (Extremity 2) averages of observed values	**Panel B: Based on five year averages at two extremities of the entire sixty year period**										
	Average of observed output (*P*)			**Average of observed yield (*Y*)**			**Average of observed area (*X*)**			**Percentage change in output due to**	
	Extremity 1	Extremity 2	ΔP	Extremity 1	Extremity 2	ΔY	Extremity 1	Extremity 2	ΔX	Yield effect	Area effect
	9.857	34.406	24.548	1113	2946	1833	8.854	11.677	2.823	87.2	12.8

Source: As in Table 1.

First, we focus on the information contained in Panel A of Table 2. Note that 1960 and 1979 respectively represent the first and last years of Phase 1; 1980 and 1997 denote those for Phase 2; 1998 and 2010 signify those for Phase 3; while 2011 and 2019 correspond to those in Phase 4. The fitted value of output has increased between the first and last years in all phases but peaked in Phase 3 (10.477 m MT, annually by .806 m MT) over the 13 year period between 1998 and 2010. The second highest level of output increase (5.473 m MT, by .304 m MT per year) was Phase 2 (1980-1997). A similar picture emerges of an increase in the fitted value of yield (657 kg ha^{-1}, annual average increase of ≈ 50.5 kg ha^{-1}) in Phase 3 (1998-2010) while it increased by 588 kg ha^{-1} (annually by ≈ 30.2 kg ha^{-1}) in Phase 2. The output and yield increased respectively by 0.872 m MT and 80 kg ha^{-1} over nine years between 2011 and 2019 (Phase 4) translating into annual average increases of 0.097 m MT and 8.9 kg ha^{-1}. Note that in Phase 1 the corresponding annual increase in output and yield were respectively 0.162 m MT and 8.3 kg ha^{-1}.

As for fitted value of gross area, the picture is somewhat different. It recorded the highest absolute increase of 1.436 m ha (annual average increase ≈ 0.072 m ha) over the 20 years between 1960 and 1979 (Phase 1) while the second highest increase of 1.369 m ha (annually by 0.105 m ha) was recorded in Phase 3 over a 13 year period. Over the 18 years in Phase 2 (1980-1997), it declined by 0.370 m ha (≈0.021 m ha annually). In the nine years of Phase 4 (2011-2019) the area under rice cultivation recorded very little change. The last two columns of Table 2 present the percentage contributions of yield and area under cultivation to rice output changes for the periods stated earlier.

We now focus on results based on Equations (5-6). A change of 3.245 m MT in fitted output in Phase 1 (column 4) resulted about evenly from increases in yield (52.3%) and output (47.7%). On the other hand, in Phase 2 and Phase 4 changes in fitted output of 5.473 m MT and 0.872 m MT respectively, entirely resulted from the yield increase counterbalancing a small negative area effect. One needs to put the results for Phase 4 in the context of an increase of less than a million m MT in fitted output over a nine-year period.

As noted earlier, both fitted output and area recorded their highest annual increases in Phase 3. Yield contributed 72.6% while area contributed 27.4% of the output increase of 10.477 m MT between 1998 and 2010. The 24.406 m MT increase in observed output between Extremity 1 and Extremity 2 of the time series originated primarily from a change in yield (87.2%) but there was also a 10.8% rise in the contribution to rice production of more land being allocated to rice cultivation. Since the 1980s, the yield effect became stronger or more dominant due to a rapid spread of the new technologies. The results for Phase 3 and those for the two extremities appear to be similar in that while the yield effect is very dominant, the area effect is still important.

Comparing values at the beginning of this series with those at its end, both increased areas, and particularly greater yield were instrumental in contributing to the growing output of rice.

3.4 Land saving effect of the Green Revolution

The Bangladeshi experience presented above does not accord with the view suggested in the existing literature that increased intensification of agriculture results in land-saving (Phalan et al., 2011a, b; Balmford et al., 2012).

Bangladesh responded to intense population pressure on arable land, and its dwindling supply per capita by: (a) initially bringing in more land under cultivation which was exhausted by the late 1960s; (b) and then by engaging in agricultural intensification of rice production with the advent of the Green Revolution. There was a slight amount of land saving in Phase 2 but a substantial increase in the gross cropped area in Phase 3 with the amount of land used for rice in Phase 4 remaining virtually stationary.

The counterfactual argument that the Green Revolution has been land-saving (see e.g., Stevenson et al., 2013) because even more land would have been needed to support Bangladesh's growing population in the absence of the Green Revolution is not relevant. The fact of the matter is that the Green Revolution has not been land saving in Bangladesh even though it has supported a much greater population than would have been able to exist. Furthermore, we are now at a juncture that the level of Bangladesh's rice production may no longer be able to be sustained for ecological and environmental reasons. The sustainability of the productivity bonus of the Green Revolution is by no means assured.

The phenomenal increase in rice yields made possible by the Green Revolution, did not result in the reduced use of land for growing rice but it was in fact, associated with greater gross land use. The quantity of land used for rice production at the beginning of Phase 2 was 10.542 m ha (Table 2, Panel A, col. 8) and at the end of Phase 4 it was 11.886 m. ha (Table 2, Panel A, col 9). Therefore, after the Green Revolution was established, the gross land area used for rice cropping rose by 1.344 m. ha or by more than 12.5%. Consequently, intensification did not result in gross land saving, although it was associated with a change in the seasonal pattern of rice growing in Bangladesh.

3.5. Observed Trends in the Variability of Bangladesh's Rice Output and Yield[4]

To consider the applicability of Conway's third hypothesis, we have utilized our basic model to determine changes in the variability of rice yields, using several simple measures of this variability. We have also done this for the aggregate level of rice production. The deviations are those away from the trend lines for each of the phases (see Figures 1 and 2).

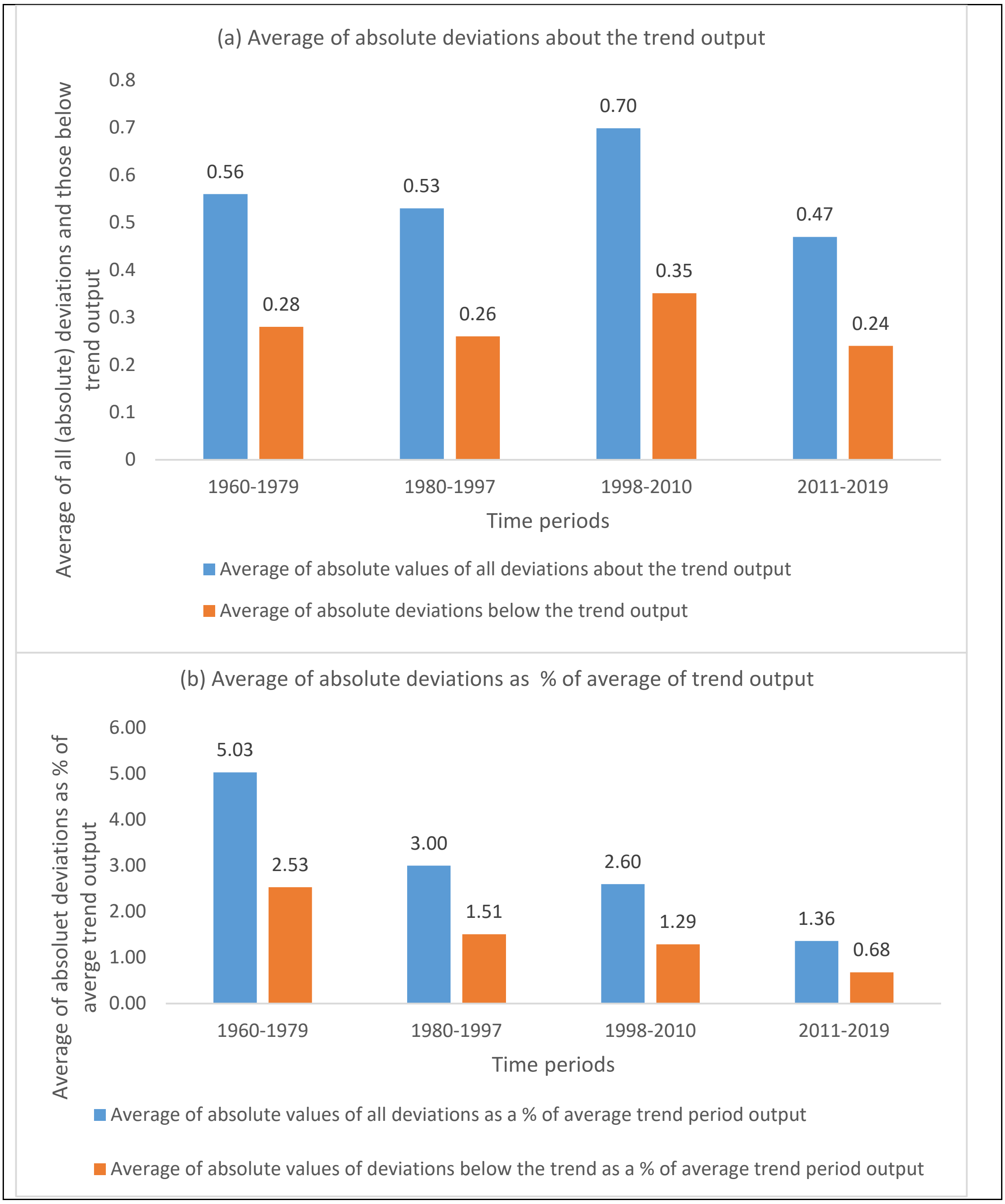

Figure 4: (a) Average of all (absolute) deviations, and those below the trend output, and (b) average of all (absolute) deviations and those below the trend as percentage of the period average of trend output for the four time periods, Bangladesh 1960-2019 (Source: Based on column 3 of Table 1).

Figure 4a depicts the averages of the absolute values of all deviations and those below the trend output. Both registered a marginal decrease during Phase 2 before registering a somewhat noticeable increase during Phase 3 and falling in Phase 4. The levels in Phase 2 and Phase 4 are quite similar. The average of all deviations and those below the trend as a percentage of average fitted output have consistently declined over time. There is a sharper decline during 1980-1997 and 2011-2019 (Figure 4b). Although the Green Revolution has not substantially reduced the absolute variation in aggregate rice output, it has resulted in a considerable reduction in its relative variability as can be seen from Figure 4b. The decline in the relative variability of rice production can be attributed to the absolute deviations being dwarfed by the increased volume of rice output.

The relative frequency of deviations below the trend output rose from 0.350 during 1960-1979[5] to 0.611 during 1980-1997 before falling to 0.384 during 1998-2010. It declined marginally to 0.333 during the 2011-2019 period. Thus, the relative frequency of the output falling below the trend appears to have followed an inverted U-shaped distribution. This indicates a lower risk of crop failure more recently. The 1960-1979 period experienced a 10% (twice in twenty years) chance of the output falling by more than 10% and >5-≤10% below the trend.

In no other periods since 1980 did the output experience such a fall below the trend. Phase 2 registered only one year i.e., 1994 when this output declined by 7.3% below the trend. In Phase 3, only 1998 recorded more than an 8.3% fall in output below the trend, due to severe flooding all over Bangladesh. In Phase 4, output fell by 5.34% below the trend because of a devastating flood in the northeastern areas in 2017.

Now let us consider the variability of rice yields. Figure 5a depicts the average of absolute values of all deviations and those below the trend. Both registered increases before falling slowly during 1998-2010 and then falling sharply during 2011-2019 indicating an inverted U-shaped pattern. The average of all deviations and those below the trend as a percentage of average yield during a period has consistently declined over time. They declined more during 1998-2010 and 2011-2019 than earlier (Figure 5b).

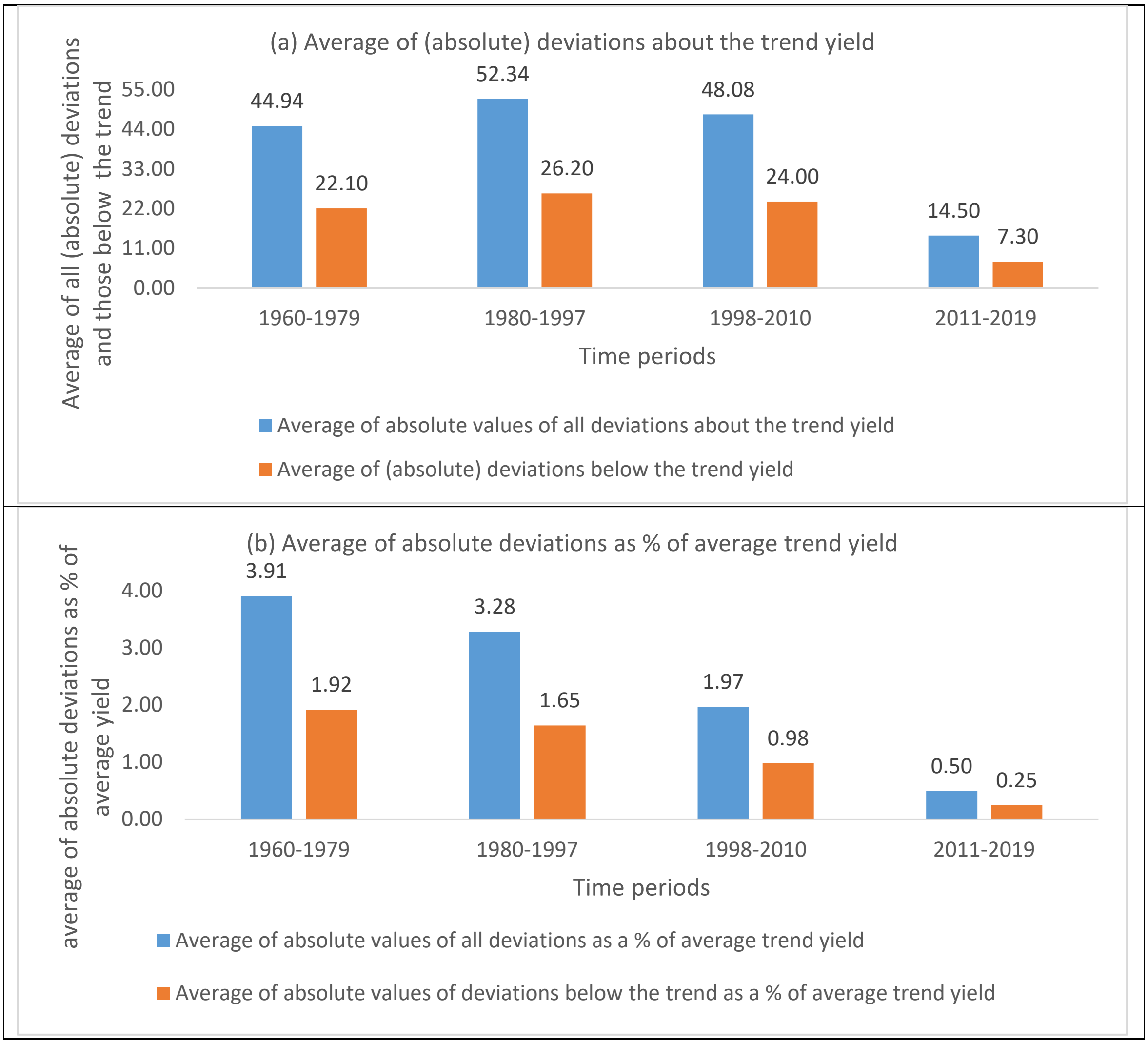

Figure 5: (a) Average of all (absolute) deviations, and those below the trend yield, and (b) average of all (absolute) deviations and those below the trend as percentage of the period average of trend yield for the four time periods, Bangladesh 1960-2019 (Source: Based on column 4 of Table 1).

3.6 A Resumé of the Main Findings

The analysis in this section so far has identified several discernible patterns. **First**, trends in area, output and yield have slowed down quite considerably in recent years. Their growth appears to have peaked in the period ending 2010. Of greater concern is the significant weakening of the trend in yield as a contributor to output growth in the last decade or so. **Secondly**, more recent output growth appears to have resulted from area expansion under HYVs via increased incidences of multiple cropping even though the yield effect remains by far the most dominant source of growth. Third**,** both rice output and yield have displayed declining variability over time. Previous studies (Alauddin and Tisdell, 1988) support the ameliorating effect of Green Revolution technologies on the variability of rice output and yield. In addition, we found that the Green Revolution did not result in a reduction in land cropped with rice.

3.7 Explaining the Observed Patterns

Given that agricultural crop production takes place under a complex system of technological environmental, and ecological conditions, a range of probable factors are at work in explaining the observed patterns presented in the preceding section.

3.7.1 Technological factors

The introduction of the Green Revolution in the late 1960s has significantly transformed crop production in Bangladesh. Consistent with the three Hayami-Ruttan (Hayami and Ruttan, 1985) typologies, Bangladesh employed all the three modes of technology transfer. Material transfer occurred via direct import of seeds of IR-5, IR-8 and IR-20 of rice at the initial stage. Subsequently, design and capacity transfer respectively took place via adaptation to local conditions, and indigenous development of different strains of rice by Bangladesh's National Agricultural Research System of Bangladesh.

Rice area and output data from the Bangladesh Rice Research Institute (http://brri.gov.bd) indicate several patterns.

1. HYVs of rice were grown over 88% of all rice land and contributed 95% of total rice output in 2018-2019. The HYV shares in the area under cultivation and in the total rice output in 1997-1998 were just over 51% and 56% respectively. By 2004–2005, the overall HYV adoption rate reached about 66%, which accounted for 82% of total rice output. HYVs accounted for more than 84% of rice area and 92% of rice output by 2014–15. The adoption of *Aus* and *Aman* HYVs of rice proceeded at a slow pace up to about the mid-1990s followed by a faster pace since then.
2. Rapid expansion of dry season irrigation propelled the adoption of *Boro* HYVs. By the mid-1970s, it reached 50% even though th*e* total land area under this crop was just over 1 m ha (10% of total rice area contributing to 18% of total rice output). Subsequently, however, both the area and HYV adoption rates of rice in the *Boro* season expanded, and more than doubled by 1997-1998 when *Boro* rice was grown on about 2.7 m ha of land (> 90% under HYVs). There was a sudden jump of .600 m ha in area under *Boro* HYVs in 1998-1999. This was against the backdrop of 0.856 m ha decrease in land under *Aman* crop

due to the devastating flood in the second half of 1998 (at the beginning of 1998-1999). By 2018-2019, *Boro* HYV cultivation expanded to about 4.9 m ha accounting for 42% of the total rice area and 55% of the total rice output. *Aus* and *Aman* crops together constitute about 58% of the total rice area and contribute 45% of the rice output.

3. For the three seasonal rice crops, output and yield followed a growth trajectory similar to the ones for their respective area under cultivation. The rapid spread of HYVs led to the yield increase underpinning the increase in output increase. The tripling of overall rice output and more than tripling of its yield since the Green Revolution resulted from the cumulative effect of these changes.
4. While *Boro* HYV rice yield has increased relatively rapidly, it seems to have settled at around the 4,000 kg ha^{-1} mark. The higher yield of the *Boro* crop was due to far greater control over the environment resulting from complete irrigation coverage and the readier availability of and accessibility to complementary inputs, including electricity and diesel for irrigation, chemical fertilizers, and pesticides and insecticides than those during the wet season. However, the yields of HYVs for the rain-fed *Aus* and *Aman* crops settled at around 2,300 and 2,500 kg ha^{-1} respectively.

Note that the annual yields are averages of yields in each season and are weighted by their respective areas under cultivation. They are likely to be less variable than for values experienced by individual farmers. The annual yields are also likely to average out their seasonal differences. The dry season rice crop has the highest yield by far coupled with a significant increase in area under its cultivation. This process has exerted an increasing influence on the annual rice yield.

3.7.2 Environmental and ecological factors

At the onset of the Green Revolution, Bangladesh had a cropping intensity[6] of < 150% (Alauddin and Tisdell, 1991). This increased to about 195% recently (BBS, 2019), mainly due to an increase in annual multiple cropping. Between the averages of 1970-1974 and 2013-2017:

- Fallow land decreased by 47.0% from 0.724 to 0.384 m ha,
- Area single cropped declined by 53.7% from 4.972 to 2.304 m ha,
- Area double cropped increased by 33.6% from 2.893 to 3.865 m ha,
- Area triple cropped increased spectacularly by 272.2% from 0.474 to 1.764 m ha.

Note that quadruple cropping since 2010 (9,000 ha in 2010 rising to 21,000 ha by 2017) has emerged as a new phenomenon and has added another dimension to agricultural intensification in Bangladesh.

In feeding its increasing population, Bangladesh has relied primarily on dry season irrigation to expand its rice production. Increasing its reliance on groundwater irrigation has been the characteristic feature of this process. In the early 1970s less than 20% (≈ 0.200 m ha) of the total irrigated area of just over one m ha originated from groundwater sources. In the last five years, 80% of the total 6 m ha irrigated cropland (≈ 4.8 m ha) utilized groundwater (BBS, 2019).

The spread of the HYV rice technology across the three crop seasons has had a stabilizing effect more recently on the annual rice yield as demonstrated by the average value of (absolute) deviations about the trend line and more importantly, by the sharp decline in average deviation as a percentage of average yield during a specific time period. Thus, the Green Revolution has had a visible impact in raising the average or expected yields of rice. While HYVs generally have a higher expected yield and greater risk than the traditional varieties when there is a lack of control of environmental conditions, in some cases they might be higher yielding with lower risks to individual famers than their traditional counterparts. As stated earlier, associated techniques and practices of farming HYVs have ensured greater control over the production environment. The biological law of environmental tolerance has been shown to be applicable to this issue (Tisdell, 1983, 2015 pp. 81-83). Furthermore, if yields and outputs between seasons are not perfectly correlated, diminished risks are likely to result due to a reduction in the relative variability (coefficient of variation). This notwithstanding, problems associated with production sustainability in the longer term may emerge as discussed earlier in this paper and elsewhere (Alauddin and Tisdell, 1991, Chapters 11-12). Leaving aside this long term problem, the multiple cropping opportunity created by the Green Revolution, may reduce the probability of annual farm income (in the present case, yield) falling below a disaster level (Anderson et al., 1977, p. 211). Multiple cropping of rice *ceteris paribus* would reduce the annual variance of yields if variations were less than perfectly correlated between seasons. However, possibly the dependence on irrigation of a large part of the annual crop [≈ 4.8 or about 42%) of the 11.6 m ha of total gross area under rice (BBS, 2019)] rather than on rain-fed moisture might be a major influence. Greater control over the availability of water should result in a lower variance in yields and in outputs. Similarly, the use of artificial fertilizers and pesticides have the potential to lower the variation in yields.

4. Resilience of the System and Probable Threats to Sustaining Bangladeshi Rice Production

Recent trends discussed in Section 3 do not adequately capture the emerging threats to increasing or sustaining Bangladesh's rice output and yield. Such threats may originate, amongst other things, from: (a) reduced genetic diversity and the consequent ecological risks; and (b) environmental risks from the spread of the Green Revolution technology and associated input use.

4.1 Loss of Genetic Diversity and Ecological Risks

The introduction of HYVs since the Green Revolution has crowded out a large number of traditional rice varieties from cultivation. Nouroallah (2016, p.52) reported that 472 of traditional *Aman* varieties and 426 of local varieties of *Boro* rice were either on their way to extinction (not planted over a significant area) or have become extinct (no longer cultivated). Hossain et al. (2013) found that *Nazir Shail*, *Lati Shail, Raja Shail, Balam, Binni, Digh*a and *Kartik Shail* [*Aman*s (late wet) season), and *Haitta, Kotoktara, Goria, Porangi, Kala Manik, Hasi Kalmi, Balam, Vaduri*, and *Aguli* [*Aus* (early wet) */Boro* (dry) season] were important rice varieties that faced extinction.

The Bangladesh Rice Research Institute (BRRI) and the Bangladesh Institute of Nuclear Agriculture (BINA) have developed over 100 rice varieties. However, as Kabir et al. (1994) reported, they rest on a narrow genetic base due to the use of few local genetic resources in the breeding program.

Genetic uniformity reduces resistance or increases susceptibility to disease and insect attacks (Hardgrove et al., 1980). The traditional varieties of rice are adaptable to ecologically and environmentally adverse conditions such as drought, salinity and tidal submergence compared to the HYVs even though some modern varieties possess some of these attributes (for further details see Tisdell et al., 2019). Substantially higher yields and somewhat shorter growing periods have favored the cultivation of HYVs relative to local varieties. However, farmers still grow some traditional varieties possessing special attributes. These include *Kalijira* (mid-north district of greater Mymensingh) and *Kataribhog* (northern district of greater Dinajpur) for their aromatic and fine grain quality, and *Motadhan* in the environmentally stressed coastal areas of Southern Bangladesh.

Based on information from BRRI (2018a, Table 1, pp. 7-9), by way of illustration, we identified parentage of 13 popular rice varieties developed by BRRI (for further details, see Tisdell et al., 2019, Table 4, p.18). The exercise revealed that four of these had exotic parentage. These include BR11 (released 1980), BR26 (released 1993), BRRI *dhan48* (released 2008), and BRRI *dhan51* (released 2008). BR3 (released 1973) and BRRI *dhan49* (released 2008) had parentages of local and exotic origin. BR23 (released 1988), BR28 (released 1995) and BR29 (released 1995), BRRI *dhan34* (released 1997) had local parentage. Thus, a significant chunk of the above varieties lacked reliance on a wide range of local genetic resources. This epitomizes the narrowness of the genetic base of the new varieties as Nouroallah (2016, p.53) reported.

"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 landrace … each Bangladeshi landrace has a high level of genetic variation, whereas the MVs are monomorphic[7]".

The information on adoption rates of BRRI and non-BRRI HYVs of rice for the three crop seasons (*Aus*, T. *Aman* and *Boro*) for 2017-2018 from BRRI (2018b, pp. 166-168, Tables 4-6) indicated that the overall (BRRI and non-BRRI) HYV adoption rate was 99.42% for *Boro*, 91.38% for *Aus* and 78.81% for T. *Aman*. The total BRRI HYV adoption rate was 69.98% for *Boro*, 65.98% for *Aus* while it was by far the lowest for the T. *Aman* crop (47.75%). The adoption rate of HYVs of Indian origin was the lowest for the *Aus* season (5.75%) and the highest for the T. *Aman* season (21.69%) while *Boro* recorded an adoption rate of 11.24%. The penetration of hybrid rice varieties is by far the deepest for the *Boro* (15.62%) season followed by 4.97% for *Aus* and 1.47% for T. *Aman* seasons.

A closer investigation of the relevant information from BRRI (2018b, pp. 166-168, Tables 4-6) and BBS (2019, p.39) suggested that two varieties of each rice crop dominate the rice production scenario in Bangladesh. Combining the BRRI (2018b) adoption rates and the area and yield data from BBS (2019, p.39), we estimated the rice area and output intensity of these varieties. Thus,

1. BRRI dhan48 (17.28%) and BRRI dhan28 (14.98%) accounted for 32.26% of the total Aus area (≈ 0.347 m ha) translating into 34.80% (≈ 0.943 m MT) of Aus rice output.
2. BRRI dhan49 (11.41%) and BR 11 (7.11%) accounted for 18.52% of the total T. Aman area (≈ 0.984 m ha) contributing to 20.56% of T. Aman rice output (≈ 2.745 m MT).

3. BRRI dhan28 (34.80%) and BRRI dhan29 (26.25%) accounted for 61.05% of the total Boro area ≈ 2.967 m ha amounting to 61.10% of Boro rice output (≈ 11.960 m MT).

Given that BRRI *dhan*28 is cultivated in both *Aus* (early wet) and *Boro* (dry) seasons, the *six* dominant varieties effectively are reduced to five. Such a high dependence only on five varieties for rice production exposes Bangladesh to a high ecological risk. This also could make it difficult to sustain rice production if these varieties succumb to new diseases given their narrow genetic base and monomorphic orientation.

Table 3: Adoption rate (%) of varieties across all rice crops, Bangladesh 2017-2018

Variety	Suitable for	Area (000 ha)	Overall adoption rate (% of gross rice area)
	Varieties with ≥ 1% adoption rate		
BRRI *dhan28*	*Aus* and *Boro* rice crops	1,913	16.47
BRRI *dhan29*	*Boro* rice crop	1,317	11.34
BRRI *dhan48*	*Aus* rice crop	192	1.65
Sub-total 1 - three dominant rice varieties for *Aus* and *Boro* rice crops		**3,422**	**29.46**
BRRI *dhan49*	T. *Aman* rice crop	626	5.39
BR11	T. Aman rice crop	390	3.36
BR22	T. Aman rice crop	231	1.99
BRRI *dhan34*	T. Aman rice crop	222	1.91
BRRI *dhan52*	T. *Aman* rice crop	171	1.47
BR23	T. *Aman* rice crop	151	1.30
Sub-total 2 - six dominant rice varieties for T. *Aman* rice crop		**1,797**	**15.48**
Sub-total 3 (varieties with ≥ 1% adoption rate)		**5,212**	**44.88**
Varieties with ≥ .5% - < 1% adoption rate			
BRRI *dhan51*	T. *Aman* rice crop	0.98	0.98
BRRI *dhan58*	*Boro* rice crop	0.92	0.92
BRRI *dhan32*	T. *Aman* rice crop	0.89	0.89
BRRI *dhan39*	T. *Aman* rice crop	0.86	0.86
BRRI *dhan41*	T. *Aman* rice crop	0.78	0.78
BRRI *dhan50*	*Boro* rice crop	0.77	0.77
BRRI *dhan*40	T. *Aman* rice crop	0.69	0.69
BR26	*Aus* crop rice crop	0.66	0.66
BRRI *dhan33*	T. *Aman* rice crop	0.61	0.61
BR16	*Boro* rice crop	0.54	0.54
Sub-total 4: Varieties with ≥ .5% - < 1% adoption rate)		**894**	**7.70**
Sub- total 5: At least 20 or so BRRI varieties with < .5% adoption rate		**757**	**6.52**
Other MVs	All rice crops	726	6.25
All Indian	All rice crops	1,818	15.65
All hybrid	All rice crops	920	7.92
All modern	**All rice crops**	10,327	**88.92**
All local varieties All rice crops		**1,287**	**11.08**
Grand total of all rice varieties		**11, 614**	**100.00**

Source: Compiled from BRRI (2018b, pp.166-168, Tables 4-6) and BBS (2019, p. 39).

While it is important to identify the high dependence on a limited number of varieties from a seasonal perspective, it is more important to do so from an overall context. Table 3 presents information on overall rice cultivation, and adoption rates of HYVs from BRRI and non-BRRI origins. The two HYVs, BRRI *dhan*28 and BRRI *dhan*29 between them account for 3.128 m ha (26.93%) of gross area under rice cultivation. An estimated 34.17% (≈ 12.398 m MT) of total rice output originates from these two varieties. Such a high dependence on only two varieties not only poses a high level of ecological risk threatening the long-term sustainability of the rice production process but also puts Bangladesh's food security at a high risk.

4.2 Environmental Risks Associated with the Spread of Green Revolution Technology

The extensive use of irrigation machinery (e.g., shallow and deep tube-wells – STWs and DTWs) has promoted a rapidly increasing groundwater dependency and this has led to a significant decline in water tables because the withdrawal of water exceeds its recharge aquifers in many areas of Bangladesh (Alauddin and Sharma, 2013; BRRI, 2019). Some parts in 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)[8]. 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 very high overall groundwater dependency of the South Asian region (Alauddin and Quiggin, 2008; Shah, 2009). Furthermore, rice not only requires much more water than other crops such as wheat, vegetables, and fruits (Hasan et al., 2019) but also the cultivation of HYVs of rice creates significant environmental damage (Sabiha et al, 2016).

The application of chemical fertilizers rose dramatically from less than 10 to 173 nutrient kg ha^{-1} of arable land between the late 1960s and the early 2000s, and increased further to 289 kg by 2016 (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 production adversely affects water quality. Inappropriate nutrient management alters plant tissue nutrient levels and morphological features of host plants (Altieri and Nicholls, 2003; Moon and Stiling, 2000). There is evidence that high levels of application of nitrogenous fertilizers to crops makes these crops more attractive to insect pests. Insect pests eat more of these crops, survive well and increase their populations (Lu et al., 2007). Consequently, crops become more vulnerable to insect attacks (Mace and Mills, 2015; Marazzi et al, 2004; Yang et al, 2016).

It is widely recognized that unintended consequences in 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 cropped ha^{-1} increased from 0.130 kg in 1990 to 0.230 kg in 1997 and then rose dramatically to 1.76 kg by 2017 (http://www.fao.org/faostat/en/QC accessed 18 April 2020). The development of HYVs of crops, particularly rice has underpinned the increased use of agro-chemicals. Consequently, Bangladeshi farmers have become increasingly dependent on external inputs and the market system (Tisdell et al., 2019; Pingali, 2012). Empirical evidence (e.g., Akter et al., 2018; Wilson and Tisdell, 2002) suggests a significant risk to human health of excessive use of agro-chemicals.

While Bangladesh has tried integrated pest management (IPM) packages developed by BRRI and the Bangladesh Agricultural University, farmers prefer to use chemical control measures because of their broad-spectrum killing properties and their instantaneous results. Application of broad-spectrum chemical insecticides kill the pest population and destroy their natural enemies (Ciancio and Mukerji, 2007) this in turn aids in the development of pesticide resistance. The consequences of the primary pest outbreak and secondary pest resurgence are increased crop injury, yield loss, and higher production costs (Dutcher et al. 1984; Braun et al. 1989)

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 on land for industrialization, infrastructure, urbanization, and human settlement. The net area cultivated has declined from about 8.7 m ha in the late 1960s to < 8 m ha in 2017-2018 (BBS, 2019).

Furthermore, Bangladesh is highly vulnerable to climate change. There are already signs that average temperatures have risen since the early 1970s, and that this is having an adverse effect on crop yields (Hasan et al., 2019; Khanal et al., 2018; Sarker et al., 2014). Thus, the two factors (continued intensification and climate change) could threaten the sustainability of Bangladesh's rice production and its rice yields[9].

5. Our Results and Conway's Prognosis

In the 1980s, Gordon Conway (1985, 1987) provided a prognosis of the ecological performance of traditional agroecosystems compared to those based on Green Revolution technologies involving the adoption of HYVs of crops (Tisdell, 2015, Ch. 4). Our results have enabled us to assess the extent to which his prognosis has been supported in the case of the adoption of HYVs of rice in Bangladesh. He emphasized two points: (1) Yields from traditional crop varieties are more sustainable than those relying on HYVs, that is the former are more resilient after being subjected to environmental or ecological shocks. (2) Yields from HYVs of crops can be expected to be more variable than in the case of traditional varieties. The first hypothesis suggests that the prospects of sustaining high yields relying on HYVs could be low.

In relation to the first matter, our results show that since the increased adoption of HYVs of rice in Bangladesh, rice yields continued to increase and are now almost three times the pre-Green Revolution level. However, recently (in the period 2011-2019) they have virtually become stationary. Whether this is a precursor to a decline in these yields is unclear. Whatever ecological shocks have been experienced in growing HYVs of rice in Bangladesh, they have not been sufficient to depress rice yields yet. However, these yields could still be quite vulnerable due to Bangladesh's heavy dependence on only a few HYVs for most of its rice production. In addition, the shrinking genetic pool for rice could make it increasingly difficult for agricultural scientists to develop new HYVs to offset those varieties, which become unproductive (Tisdell, 2015, Ch. 4).

As for Conway's third hypothesis (stated above) our results indicate that (on average) absolute variations in the yields of rice in Bangladesh regarding trends were higher in the periods 1980-1997 and 1998-2010 compared to the 1960-1979 period when there was little adoption of HYVs of rice. However, in the latest period (2011-2019), these variations were much lower than in any prior period. Rice growers, therefore, seem to have had reduced control over their yields using HYVs compared to their reliance on traditional varieties in the earlier years of the Green Revolution in terms of the variation in **absolute** yields but greater control has been achieved more recently. These results are partially in accordance with Conway's third hypothesis.

However, it may be more relevant to consider trends in change in the relative deviations of rice yields about the trends. Compared to the pre-Green Revolution situation these displayed a decline in each succeeding period of adoption of HYVs of rice. This indicates that Bangladesh's rice growers on average had more control over their relative rice yields following the Green Revolution than prior to it. For example, their greater reliance on irrigated rice crops rather than rain-fed crops should have been an important contribution to this result. Although the agroecosystem analysis of Conway is analytically helpful, we need a wider focus on factors influencing yields. Conway basically concentrated on the possible ecological impacts of the Green Revolution on yields. However, they are also influenced by the prices of the commodities involved as was pointed out by Pingali (2012). A range of factors including ecological and environmental changes, technological change, and input and output price relativities can alter rice yields. These influences tend to be interdependent and as a result, the dynamics of changes in yields involve a complex interactive system, as is illustrated in Fig. 6.

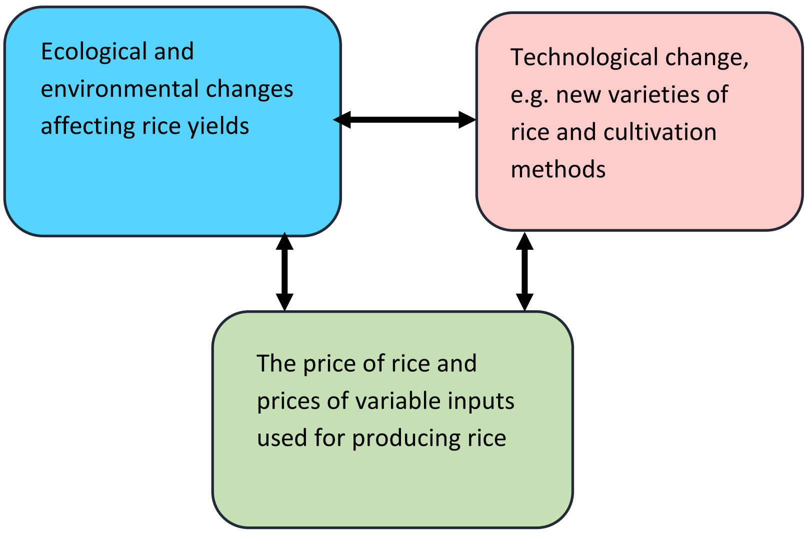

Figure 6: A trio of factors that influence rice yields

Aggregate (average) yields of rice can also vary with the quality of land allocated to rice production. *Ceteris paribus*, allocating additional land of lower quality for the growing of rice will reduce its aggregate average yield. We do not have enough data to disentangle the relative influences of each of these factors on rice yields in Bangladesh, but it is necessary to recognize their relevance.

On the other hand, the impacts on yields and their variability of alterations in ecological and environmental conditions or technological change occur because of shifts in the marginal physical production schedule for rice or changes in its form. Shifts in the production function for rice generate these impacts. While agricultural scientists usually pay attention to these types of influences, they generally do not consider the impact which changing prices (both of inputs and of outputs) can have on the magnitude of crop yields but the latter can be significant.

6. Conclusion

This research confirms that increases in yields of rice have been by far the main contributor to the growth in rice output in Bangladesh since the establishment of the Green Revolution. Furthermore, yields have continued to rise since its establishment until recently. In the last few years, they have become almost stationary. We explored the possibility that this stationarity might be a precursor to their decline, as well as the possible impact on yields of a major environmental or ecological shock. We suggested that because of the high dependency of Bangladesh on just a few HYVs of rice (and its shrinking gene pool) that the productivity of its rice crop could be vulnerable to major ecological and environmental shocks. It was pointed out that Conway (1985, 1987) has hypothesized that yields employing modern agroecosystems are much less sustainable (less resilient) than traditional ones. The ecological and environmental shocks to completely destabilize Bangladesh’s rice agroecosystem and make it unsustainable may still occur.

As for the impact of the Green Revolution on the variability of rice yields in Bangladesh, we found that until recently, their absolute variability was higher after the early establishment of the Green Revolution than prior to it. This provides some support for Conway’s hypothesis that yields are prone to be more variable when modern rather than traditional agricultural systems are adopted. On the other hand, it was also found that relative variations in rice yields away from trend values of yields were smaller after the Green Revolution was well established than before it and they continued to fall as the adoption of Green Revolution technologies became more widespread. We discussed possible reasons for this result.

This paper pointed out that changes in yields do not depend only on variations in ecological and environmental conditions or technological change. Yields also vary because of changes in prices, and the aggregate average yield of a crop can alter as the productive quality of land added to or subtracted from its cultivation is varied. Thus, a complex set of forces and interactions bring about changes in the yields of crops. Apart from the empirical results reported in this article, a significant contribution of this research has been to identify the full range of factors, which cause the yields of crops to alter, and to relate these to standard types of micro-economic modelling. Because Bangladesh depends heavily on its rice output for its supply of food, its food security will be undermined if its rice output becomes unsustainable.

This is the first long-term empirical study of the impact of the Green Revolution on the level and the sustainability of rice yields and their variability. It identifies the increased cultivation of rice in the dry season (relying on underground water supplies) as the main source of increased annual rice yields and rice production in Bangladesh. Major ecological and environmental threats (some of which have had little or no exposure in the economic literature) to the sustainability of rice yields and the level of rice production were specified.

Our empirical analysis has enabled us to evaluate the pioneering predictions of Gordon Conway about the effects of the Green Revolution on the nature of crop yields in a long-period context. This study underscores the importance of a trio of general factors, which determine rice yields. A holistic analysis requires these all to be considered, but the economic influences stated above are often overlooked by non-economists in assessing the influences on the level of crop yields. On the other hand, economists fail to take account of environmental and ecological considerations. This article also shows how dependent Bangladesh is on its rice production for its food security. Failure to sustain Bangladesh's level of rice production is likely to result in a sharp increase in the incidence of poverty in Bangladesh. This adds to the relevance of this study. Furthermore, the analytical framework employed in this study can be adapted to other countries with similar biophysical and demographic characteristics.

End notes

1. Testing Conway's 4th hypothesis on income distributional outcomes is an important area, which warrants a separate in-depth investigation.
2. Yunus et al (2019, p. 8) projects a per capita daily rice consumption of 396.6 g for 2018 which translates into an annual figure of 144.8 kg.
3. This is like the product differentiation rule to measure the relative contribution of changes in yield (Yt) and area planted (Xt) to the changes in the volume of rice output (Pt). The relevant function is Pt = Yt. Xt. Therefore, P′t = Yt X′t + Xt Y′t.

4. We do not provide any detailed statistical results here for brevity, but these are available upon request.
5. Calculated as: number of years with deviations below the trend ÷ number of total years in the period. For example, the 1960-1979 period with deviations below the trend in seven out of twenty years gives a relative frequency = 7 ÷ 20 = 0.350.
6. [Gross cropped area (including multiple cropping)] ÷ [Net-cropped area] x 100.
7. Showing little or no variation in morphology or phenotype (Oxford Dictionary).
8. 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.
9. These apart, one could not rule out the possibility of climate change induced sea-level rise. Given the low elevation of much of Bangladesh, this is likely have an adverse effect on all of Bangladesh's food production. However, an in-depth investigation of the impact of sea level rise on Bangladeshi food production is beyond the scope of this study.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research authorship and/or publication of this article.

Acknowledgements

With usual *caveats* we would like to acknowledge our gratitude to Md Mahbubur Rahman, Md Shahiduzzaman and Evelyn Smart for useful research assistance, and to Zeenatul Islam for important pieces of information.

References

Alauddin, M. and Quiggin, J. (2008). Agricultural intensification, irrigation and the environment in South Asia: Issues and policy options, Ecological Economics, 65, 111-124. https://doi.org/10.1016/j.ecolecon.2007.06.004

Alauddin, M. and Sarker, M.A.R. (2014). Climate change and farm-level adaptation decisions and strategies in drought-prone and groundwater-depleted areas of Bangladesh: An empirical investigation, Ecological Economics, 106, 204-213. https://doi.org/10.1016/j.ecolecon.2014.07.025

Alauddin, M., Sarker, M.A.R., Islam, Z. and Tisdell, C.A. (2020). Adoption of alternate wetting and drying (AWD) irrigation as a water-saving technology in Bangladesh: Economic and environmental considerations, Land Use Policy, 91, 104430. https://doi.org/10.1016/j.landusepol.2019.104430

Alauddin, M. and Sharma, B.R. (2013). Inter-district rice water productivity differences in Bangladesh: An empirical exploration and implications, Ecological Economics, 93, 210-218. https://doi.org/10.1016/j.ecolecon.2013.05.015

Alauddin, M. and Tisdell, C.A. (1988). Impact of new agricultural technology on the instability of foodgrain production and yield: Data analysis for Bangladesh and its districts, Journal of Development Economics, 29, 199-227. DOI: 10.1016/0304-3878(88)90035-1.

Alauddin, M. and Tisdell, C.A. (1991). The Green Revolution and Economic development: The Process and Its Impact in Bangladesh, London: Macmillan.

Altieri MA, Nicholls C I. (2003). Soil fertility management and insect pests: Harmonizing soil and plant health in agroecosystems. *Soil and Tillage Research*, 72, 203–211. https://doi.org/10.1016/S0167-1987(03)00089-8

Anderson, J.R., Dillon, J.L. and Hardakar, J.B. (1977). *Agricultural Decision Analysis*, Ames, Iowa: Iowa University Press.

Balmford, A. Green, R.E. and Phalan, B. (2012). What conservationists need to know about farming. *Proceedings of the Royal Society B.*, *297*, 2714-2724. https://doi.org/10.1098/rspb.2012.0515

Barbier, E.B. (1987). The concept of sustainable economic development. *Environmental Conservation*, 14, 101-110. https://doi.org/10.1017/S0376892900011449

BBS (2015). *Population Projection of Bangladesh: Dynamics and Trends 2011-2061*, Dhaka: Bangladesh Bureau of Statistics.

BBS (2017). *Household Income and Expenditure Survey, 2016*, Dhaka: Bangladesh Bureau of Statistics.

BBS (2019). *Yearbook of Agricultural Statistics 2018*, Dhaka: Bangladesh Bureau of Statistics.

Bishwajit, G., Sarker, S., Kpoghomou, M-A et al., Gao, H., Jun, L., Yin, D. and Ghosh, S. (2013). Self-sufficiency in rice and food security: A South Asian perspective, *Agriculture & Food Security* (Open Access) http://www.agricultureandfoodsecurity.com/content/2/1/10 .

BPC (2018). *Bangladesh Delta Plan 2100, Baseline Studies*, Vol. 4. Agriculture Food Security and Nutrition, Dhaka: General Economics Division, Bangladesh Planning Commission.

Braun A.R., Bellotti A.C., Guerrero, J.M. and Weilson. L.T. (1989). Effect of predator exclusion on cassava infest with tetranychid mites (*Acari: Tetranychidae*). *Environmental Entomology*, 18, 711-714. https://doi.org/10.1093/ee/18.4.711

BRRI (2018a). Adhunik Dhaner Chash (Modern Rice Cultivation), Twenty-first edition, Bangladesh Rice Research Institute, Gazipur 1701.

BRRI (2018b). *Annual Report of the Bangladesh Rice Research Institute 2017-2018*. Bangladesh Rice Research Institute, Gazipur 1701.

BRRI (2019). *Annual Report of the Bangladesh Rice Research Institute 2018-2019*. Bangladesh Rice Research Institute, Gazipur 1701.

Burney, J.A., Davis., S.J. and Lobell, D.B. (2010). Greenhouse gas mitigation by agricultural intensification. *Proceedings of the National Academy of Sciences*, *107*, 12052–12057. https://doi.org/10.1073/pnas.0914216107

Ciancio, A. and Mukerji, K.G. (2007). *General Concepts in Integrated Pest and Disease* Management. Springer Netherlands, Dordrecht.

Conway, G.R. (1985). Agroecosystem analysis, *Agricultural Administration*, 20, 31-55. https://doi.org/10.1016/0309-586X(85)90064-0

Conway, G.R. (1987). The properties of agroecosystems, *Agricultural Systems*, 24, 95-117. https://doi.org/10.1016/0308-521X(87)90056-4

Dittrich, V., Streibert, P. and Bathe, P.A. (1974). An old case reopened: mite simulation by insecticide residues. *Environmental Entomology*, 3, 534-540 https://doi.org/10.1093/ee/3.3.534

Gujarati, D.N. (2003). *Basic Econometrics*, Boston, MA: McGraw-Hill (4th edition).

Hargrove, T.R.; Coffman, W.R.; Cabanilla, V.L. (1980). Ancestry of improved cultivars of Asian rice. *Crop Science*, *20*, 721–727. https://doi.org/10.2135/cropsci1980.0011183X002000060011x

Hasan, M.M., Alauddin, M., Sarker, M.A.R., Jakaria, M. and Alamgir, M. (2019). Climate sensitivity of wheat yield in Bangladesh: Implications for the United Nations sustainable development goals 2 and 6, *Land Use Policy, 87*, 104023. https://doi.org/10.1016/j.landusepol.2019.104023

Hayami, Y. and Ruttan, V.W. (1985). *Agricultural Development: An International Perspective*, Baltimore, Johns Hopkins University Press.

Hossain, M.; Jaim, W.H.M.; Alam, M.S.; Rahman, A.N.M. (2013). *Rice Biodiversity in Bangladesh: Adoption, Diffusion and Disappearance of Varieties*. A Statistical Report from Farm-survey in 2005; BARC (Bangladesh Agricultural Research Council) Research and Evaluation Forum: Dhaka, Bangladesh,

Islam, S. F. and Talukder, R. K. (2017). Projections of food demand and supply in Bangladesh: implications on food security and water demand. International *Journal of Sustainable Agricultural Management and Informatics, 3*(2), 125-153. https://dx.doi.org/10.1504/IJSAMI.2017.085663

Kabir, M.A.; Sarkar, H.C.; Salam, M.A.; Hoque, M.; Miah, N.M. (1994). Genetic composition of improved rice varieties in Bangladesh. *Bangladesh Rice Journal*, 5, 95–110.

Khanal, U., Wilson, C., Hoang, V-N. and Lee, B. (2018). Farmers' Adaptation to Climate Change, Its Determinants and Impacts on Rice Yield in Nepal, *Ecological Economics*, *144*, 139-147. https://doi.org/10.1016/j.ecolecon.2017.08.006

Mace K.C. and Mills, N.J. (2015). Response of walnut aphid populations to increasing foliar nitrogen content. *Agricultural and Forest Entomology 17*, 277–284. https://doi.org/10.1111/afe.12103

Marshall, D.R. (1977). The advantages and hazards of genetic homogeneity. *Annals of the New York Academy of Sciences, 287*, 1–20. doi: 10.1111/j.1749-6632.1977.tb34226.x.

Marazzi C, Patrian B, Stadler E. (2004). Secondary metabolites of the leaf surface affected by sulphur fertilization and perceived by the diamondback moth. *Chemoecology, 14*, 81–86. https://doi.org/10.1007/s00049-003-0264-y

Moon DC, Stiling P. (2000). Relative importance of abiotically induced direct and indirect effects on a salt-marsh herbivore. *Ecology, 81*, 470–481. https://doi.org/10.1890/0012-9658(2000)081[0470:RIOAID]2.0.CO;2

Nourollah, A. (2016). Genetic diversity, genetic erosion and conservation of the two cultivated rice species (oryza sativa and oryza glabarrima) and their close wild relatives. In: Ahuja, M.R. and Jain, S.M. (Eds.). *Genetic Diversity and Erosion in Plants: Case Histories* (Volume 2), pp.25-74, Switzerland: Springer.

Phalan, B., Balmford, A., Green, R.e. and Scharlemann (2011a) Minimizing harm to biodiversity of producing more food globally, *Food Policy, 36*, 562-571. https://doi.org/10.1016/j.foodpol.2010.11.008

Phalan, B, Onial, M., Balmford, A. and Green, R.E. (2011b). Reconciling food production and biodiversity conservation: land sharing and land sparing compared, *Science, 333***,** 1289-1291. doi: 10.1126/science.1208742

Pingali, P. (2012). Green Revolution: Impacts, limits, and the path ahead. Proceedings of the *National Academy of Sciences, 109*(31), 12302-12308. https://doi.org/10.1073/pnas.0912953109

Ringler, C., Cenacchi, N., Koo, J., Robertson, R.D., Fisher, M., Cox, C.M.; Perez, N.D., Garrett, K. and Rosegrant, M.W. (2014). Sustainable agricultural intensification: The promise of innovative farming practices. In 2013 *Global Food Policy Report*. Eds. Marble, Andrew and Fritschel, Heidi. Chapter 4 (pp. 43-52). Washington, D.C.: International Food Policy Research Institute (IFPRI). http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/128047.

Roumasset, J. (1976). *Rice and Risk*. Amsterdam: North Holland

Sabiha, N., Salim, R., Rahman, S., Rola-Rubzen, F., 2016. Measuring environmental sustainability in agriculture: A composite environmental impact index approach, *Journal of Environmental Management, 166*, 84-93. https://doi.org/10.1016/j.jenvman.2015.10.003

Sarker, M.A.R., Alam, K. and Gow, J. (2014). Assessing the effects of climate change on rice yields: An econometric investigation using Bangladeshi panel data, *Economic Analysis and Policy, 44*, 405-416. https://doi.org/10.1016/j.eap.2014.11.004

Simolders, H. (2006). *Enhancing Farmers' Role in Crop Development. Framework Information for Participatory Plant Breeding in Farmers Field Schools*; Centre for Genetic Resources, Wageningen University and Research Centre: Wageningen, The Netherlands.

Stevenson, J.R., Villoria, N., Byerlee, D., Kelley, T. and Marwedia, M. (2013). Green Revolution research saved an estimated 18 to 27 million hectares of land from being brough into agricultural production. *Proceedings of the National Academy of Sciences, 110*(21), 83-63-8368. https://doi.org/10.1073/pnas.1208065110.

Tisdell, C.A. (1983). The biological law of tolerance, average biomass and production in an uncontrolled environment. International Journal of Ecology and Environmental Sciences, 9, 99-109.

Tisdell, C.A. (2015). Sustaining Biodiversity and Ecosystem Functions: Economic Issues. Cheltenham, UK and Northampton, USA: Edward Elgar Publishing.

Tisdell, C.A. (2017). Economics and Environmental Change: The Challenges We Face, Cheltenham, UK and Northampton, USA: Edward Elgar Publishing.

Tisdell, C.A., Alauddin, M., Sarker, M.A.R. and Kabir, M.A. (2019). Agricultural diversity and sustainability: general features and Bangladeshi illustrations, Sustainability, 11, 6004; doi: 10.3390/su11216004.

Wilson, C. and Tisdell, C.A. (2002). Why farmers continue to use pesticides despite environmental, health and sustainability costs, Ecological Economics 39, 449–462. https://doi.org/10.1016/S0921-8009(01)00238-5Wooldridge, J. M. (2020). *Introductory Econometrics: A Modern Approach*. Boston, MA: Cengage Books.

Yunus, M., Rashid, S. and Chowdhury, S. (2019). *Per capita rice consumption in Bangladesh: Available estimates and IFRI's validation survey results*, Bangladesh Integrated Food Policy Research Program Working Paper 003. Washington, D.C.: International Food Policy Research Institute.

Yang, Y-J., Li, X-D., Xu, H-X., Zheng, X-S. and Lu, Z-X. (2016). Nitrogen fertilizer promotes the resurgence of Nilaparvata lugens (Hemiptera: Delphacidae) induced by deltamethrin on Bt rice and non-Bt rice lines. *Acta Entomologica Sinica 59*, 1263-1271. https://www.cabdirect.org/cabdirect/abstract/20173042751

PREVIOUS WORKING PAPERS IN THE SERIES

ECONOMICS, ECOLOGY AND ENVIRONMENT

For a list of working papers 1-100 in this series, visit the following website:
http://www.uq.edu.au/economics/PDF/staff/Clem_Tisdell_WorkingPapers.pdf or see lists in papers 101 on.

101. Knowledge and Willingness to Pay for the Conservation of Wildlife Species: Experimental Results Evaluating Australian Tropical Species, by Clem Tisdell and Clevo Wilson, May 2004.
102. Antarctic Tourists, Wildlife and the Environment: Attractions and Reactions to Antarctica, by Clem Tisdell, May 2004.
103. Birds in an Australian Rainforest: Their Attraction for Visitors and Visitors' Ecological Impacts, by Clem Tisdell and Clevo Wilson, May 2004.
104. Nature-Based Tourism and the Valuation of its Environmental Resources: Economic and Other Aspects by Clem Tisdell, May 2004.
105. Glow Worms as a Tourist Attraction in Springbrook National Park: Visitor Attitudes and Economic Issues, by Clem Tisdell, Clevo Wilson and David Merritt, July 2004.
106. Australian Tropical Reptile Species: Ecological Status, Public Valuation and Attitudes to their Conservation and Commercial Use, by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, August 2004.
107. Information and Wildlife Valuation: Experiments and Policy, by Clem Tisdell and Clevo Wilson, August 2004.
108. What are the Economic Prospects of Developing Aquaculture in Queensland to Supply the Low Price White Fillet Market? Lessons from the US Channel Catfish Industry, by Thorbjorn Lyster and Clem Tisdell, October 2004.
109. Comparative Public Support for Conserving Reptile Species is High: Australian Evidence and its Implications, by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, October 2004.
110. Dependence of public support for survival of wildlife species on their likeability by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, October 2004.
111. Dynamic Processes in Contingent Valuation: A Case Study Involving the Mahogany Glider by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, November 2004.
112. Economics, Wildlife Tourism and Conservation: Three Case Studies by Clem Tisdell and Clevo Wilson, November 2004.
113. What Role Does Knowledge of Wildlife Play in Providing Support for Species' Conservation by Clevo Wilson and Clem Tisdell, December 2004.
114. Public Support for Sustainable Commercial Harvesting of Wildlife: An Australian Case Study by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, December 2004.
115. Endangerment and Likeability of Wildlife Species: How Important are they for Proposed Payments for Conservation by Clem Tisdell, Hemanath Swarna Nantha and Clevo Wilson, December 2004.
116. How Knowledge Affects Payment to Conserve and Endangered Bird by Clevo Wilson and Clem Tisdell, February 2005.
117. Public Choice of Species for the Ark: Phylogenetic Similarity and Preferred Wildlife Species for Survival by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, March 2005.
118. Economic Incentives for Global Conservation of Wildlife: New International Policy Directions by Clem Tisdell, March 2005.
119. Resource Entitlements of Indigenous Minorities, Their Poverty and Conservation of Nature: Status of Australian Aborigines, Comparisons with India's Tribals, Theory and Changing Policies Globally by Clem Tisdell, March 2005.
120. Elephants and Polity in Ancient India as Exemplified by Kautilya's *Arthasastra* (Science of Polity) by Clem Tisdell, March 2005.
121. Sustainable Agriculture by Clem Tisdell, April 2005.
122. Dynamic Processes in the Contingent Valuation of an Endangered Mammal Species by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, April 2005.
123. Knowledge about a Species' Conservation Status and Funding for its Preservation: Analysis by Clem Tisdell, June 2005.
124. Public Valuation of and Attitudes towards the Conservation and Use of the Hawksbill Turtle: An Australian Case Study by Clem Tisdell, Hemanath Swarna Nantha and Clevo Wilson, June 2005.

125. Comparison of Funding and Demand for the Conservation of the Charismatic Koala with those for the Critically Endangered Wombat *Lasiorhinus krefftii* by Clem Tisdell and Hemanath Swarna Nantha, June 2005.
126. Management, Conservation and Farming of Saltwater Crocodiles: An Australian Case Study of Sustainable Commercial Use by Clem Tisdell and Hemanath Swarna Nantha, August 2005.
127. Public Attitudes to the Use of Wildlife by Aboriginal Australians: Marketing of Wildlife and its Conservation by Clem Tisdell and Hemanath Swarna Nantha, August 2005.
128. Linking Policies for Biodiversity Conservation with Advances in Behavioral Economics by Clem Tisdell, August 2005.
129. Knowledge about a Species' Conservation Status and Funding for its Preservation: Analysis by Clem Tisdell, August 2005.
130. A Report on the Management of Saltwater Crocodiles (*Crocodylus porosus*) in the Northern Territory: Results of a Survey of Pastoralists by Clem Tisdell, Clevo Wilson and Hemanath Swarna Nantha, September 2005.
131. Crocodile Farms and Management of Saltwater Crocodiles in Northern Territory: Results of a Survey of NT Crocodile Farmers Plus Analysis of Secondary Information by Clem Tisdell, September 2005.
132. The Environment and the Selection of Aquaculture Species and Systems: An Economic Analysis by Clem Tisdell, October 2005.
133. The History and Value of the Elephant in Sri Lankan Society by Ranjith Bandara and Clem Tisdell, November 2005.
134. Economics of Controlling Livestock Diseases: Basic Theory by Clem Tisdell, November 2006.
135. Poverty, Political Failure and the Use of Open Access Resources in Developing Countries by Clem Tisdell, November 2006.
136. Global Property Rights in Genetic Resources: An Economic Assessment by Clem Tisdell, November 2006.
137. Notes on the Economics of Fish Biodiversity: Linkages between Aquaculture and Fisheries by Clem Tisdell, November 2006.
138. Conservation of the Proboscis Monkey and the Orangutan in Borneo: Comparative Issues and Economic Considerations by Clem Tisdell and Hemanath Swarna Nantha, March 2007.
139. Economic Change and Environmental Issues: Policy Reforms and Concerns in Australian Agriculture, by Clem Tisdell, April 2007.
140. Institutional Economics and the Behaviour of Conservation Organizations: Implications for Biodiversity Conservation by Clem Tisdell, March 2007
141. Poverty, Policy Reforms for Resource-use and Economic Efficiency: Neglected Issues by Clem Tisdell, May 2007.
142. The State of the Environment and the Availability of Natural Resources by Clem Tisdell, May 2007.
143. Economics of Pearl Oyster Culture by Clem Tisdell and Bernard Poirine, July 2007.
144. The Economic Importance of Wildlife Conservation on the Otago Peninsula – 20 Years on by Clem Tisdell, November, 2007.
145. Valuing the Otago Peninsula: The Economic Benefits of Conservation by Clem Tisdell, November 2007.
146. Policy Choices about Agricultural Externalities and Sustainability: Diverse Approaches, Options and Issues by Clem Tisdell, November, 2007.
147. Global Warming and the Future of Pacific Island Countries by Clem Tisdell, November 2007.
148. Complex Policy Choices about Agricultural Externalities: Efficiency, Equity and Acceptability by Clem Tisdell, June 2008.
149. Wildlife Conservation and the Value of New Zealand's Otago Peninsula: Economic Impacts and Other Considerations by Clem Tisdell, June 2008.
150. Global Property Rights in Genetic Resources: Do They Involve Sound Economics? Will They Conserve Nature and Biodiversity? By Clem Tisdell, August 2008.
151. Supply-side Policies to Conserve Biodiversity and Save the Orangutan from Oil Palm Expansion: An Economic Assessment. By Clem Tisdell and Hemanath Swarna Nantha, September, 2008.
152. The Orangutan-Oil Palm Conflict: Economic Constraints and Opportunities for Conservation by Hemanath Swarna Nantha and Clem Tisdell, October 2008.
153. Economics, Ecology and the Development and Use of GMOs: General Considerations and Biosafety Issues by Clem Tisdell, October 2008.
154. Agricultural Sustainability and the Introduction of Genetically Modified Organisms (GMOs) by Clem Tisdell, February, 2009.
155. Notes on Biodiversity Conservation, The Rate of Interest and Discounting by Clem Tisdell, April, 2009.
156. Is Posner's Principle of Justice an Adequate Basis for Environmental Law? by Clem Tisdell, June 2009.

157. The Sustainability of Cotton Production in China and Australia: Comparative Economic and Environmental Issues By Xufu Zhao and Clem Tisdell, June 2009.
158. The Precautionary Principle Revisited: Its Interpretations and their Conservation Consequences by Clem Tisdell, September, 2009.
159. The Production of Biofuels: Welfare and Environmental Consequence for Asia by Clem Tisdell, September, 2009.
160. Environmental Governance, Globalisation and Economic Performance by Clem Tisdell, November 2009.
161. Managing Forests for Sustainable Economic Development: Optimal Use and Conservation of Forests by Clem Tisdell, February 2010.
162. Comparative Costs and Conservation Policies for the Survival of the Orangutan and Other Species: Includes an Example by Clem Tisdell and Hemanath Swarna Nantha, May 2010.
163. Notes on the Economics of Control of Wildlife Pests by Clem Tisdell, May 2010
164. Are tourists rational? Destination decisions and other results from a survey of visitors to a North Queensland natural site – Jourama Falls by Clem Tisdell, June 2010.
165. Conservation Value by Clem Tisdell, June 2010.
166. The Influence of Public Attitudes on Policies for Conserving Reptiles by Clem Tisdell, July 2010.
167. Core Issues in the Economics of Biodiversity Conservation by Clem Tisdell, July 2010.
168. The Survival of a Forest-Dependent Species and the Economics of Intensity of Logging: A Note by Clem Tisdell, August 2010.
169. A Case Study of an NGOs Ecotourism Efforts: Findings Based on a Survey of Visitors to its Tropical Nature Reserve by Clem Tisdell, August, 2010.
170. Sharing Nature's Wealth through Wildlife Tourism: Its Economic, Sustainability and Conservation Benefits by Clem Tisdell, August, 2010
171. Economic Growth and Transition in Vietnam and China and its Consequences for their Agricultural Sectors: Policy and Agricultural Adjustment Issues by Clem Tisdell, September, 2010.
172. World Heritage Listing of Australian Natural Sites: Effects on Tourism, Economic Value and Conservation by Clem Tisdell, October, 2010.
173. Antarctic tourism: Environmental concerns and the importance of Antarctica's natural attractions for tourists by Clem Tisdell, October 2010.
174. Sustainable Development and Intergenerational Equity: Issues Relevant to India and Globally by Clem Tisdell, November 2010
175. Selective Logging and the Economics of Conserving Forest Wildlife Species e.g. Orangutans by Clem Tisdell, September 2011.
176. Economics, Ecology and GMOs: Sustainability, Precaution and Related Issues by Clem Tisdell, September 2011.
177. Economics of Controlling Vertebrate Wildlife: The Pest-Asset Dichotomy and Environmental Conflict by Clem Tisdell. September 2011
178. Ecotourism Experiences Promoting Conservation and Changing Economic Values: The Case of Mon Repos Turtles by Clem Tisdell, June 2012.
179. Sustainable Development Planning: Allowing for Future Generations, Time and Uncertainty by Clem Tisdell, June 2012.
180. Biodiversity Change and Sustainable Development: New Perspectives by Clem Tisdell, June 2012.
181. Economic Benefits, Conservation and Wildlife Tourism by Clem Tisdell, June 2012.
182. Conserving Forest Wildlife and other Ecosystem Services: Opportunity Costs and the Valuation of Alternative Logging Regimes by Clem Tisdell, June 2012.
183. Sustainable Agriculture – An Update by Clem Tisdell, December, 2012.
184. Ecosystem Services: A Re-examination of Some Procedures for Determining their Economic Value by Clem Tisdell, December 2012.
185. Biodiversity Conservation: Concepts and Economic Issues with Chinese Examples by Clem Tisdell, December 2012.
186. The Nature of Ecological and Environmental Economics and its Growing Importance by Clem Tisdell, December 2012.
187. Sustaining Economic Development and the Value of Economic Production: Different Views and Difficult Problems by Clem Tisdell, December 2012
188. Climate Change – Predictions, Economic Consequences, and the Relevance of Environmental Kuznets Curves by Clem Tisdell, December 2012.
189. Managing Ecosystem Services for Human Benefit: Economic and Environmental Policy Challenges by Clem Tisdell and Dayuan Xue, April 2013.
190. Nature-based Tourism in Developing Countries: Issues and Case Studies by Clem Tisdell. May 2013

191. Three Questionnaires Used in Evaluating the Economics of Conserving Australia's Tropical Wildlife Species and the Procedures Adopted by Clem Tisdell and Clevo Wilson, January 2014.
192. The Neolithic Revolution and Human Societies: Diverse Origins and Development Paths by Serge Svizzero and Clem Tisdell. April 2014.
193. Genetic Erosion in Traditional Food Crops in the Pacific Islands: Background, Socioeconomic Causes and Policy Issues by Clem Tisdell, April 2014.
194. The Opportunity Cost of Engaging in Reduced-Impact Logging to Conserve the Orangutan: A Case Study of the Management of Deramakot Forest Reserve, Sabah, Malaysia by Hemanath Swarna Nantha, April 2014.
195. The Financial and Political Opportunity Costs of Orangutan Conservation in the Face of Oil-Palm Expansion by Hemanath Swarna Nantha, April 2014.
196. 'Genetic Erosion in Traditional food Crops in the Pacific Islands: Background, Socioeconomic Causes and Policy Issues' – WP193 Amended by Clem Tisdell, July 2014.
197. Hunter-Gatherer Societies: Their Diversity and Evolutionary Processes by Serge Svizzero and Clem Tisdell, August 2014.
198. Agricultural Development and Sustainability: A Review of Recent and Earlier Perspectives by Clem Tisdell, January, 2015.
199. Marine Ecosystems and Climate Change: Economic Issues by Clem Tisdell, August 2015.
200. Parochial Conservation Practices and the Decline of the Koala by Clem Tisdell, Harriet Preece, Sabah Abdullah and Hawthorne Beyer, October 2015.
201. The Economic Development and the Rise and Fall of Únětice Populations: A Case of Ecologically Unsustainable Economic Growth? Initial Thoughts by Clem Tisdell and Serge Svizzero, October 2016
202. Input Shortages and the Lack of Sustainability of Bronze Production by the Únětice by Serge Svizzero and Clem Tisdell, November 2016
203. Economic Reforms and Carbon Dioxide Emissions in European and Central Asian Transition Economies by Rabindra Nepal, Clem Tisdell and Tooraj Jamasb, February, 2017.
204. Were Desert Kites Used Exclusively as Driven Hunting Structures? Unresolved Issues and Alternative Interpretations of the Evidence – Socio-economic and Biological Considerations (A Draft) by Serge Svizzero and Clem Tisdell, February 2017.
205. The Demise of the Únětice Culture due to the Reduced Availability of Natural Resources for Bronze Production (A Draft) by Serge Svizzero and Clem Tisdell, August 2017.
206. Koala Extinction: Inefficient Conservation Strategies Identified and Examined – Moral and Ethical Issues by Clem Tisdell, November 2017.
207. Public finance for renewable energy use and for the renewable energy sector's development: externalities, sustainability and other issues by Clem Tisdell, March 2019.
208. India's Biodiversity Conservation Responses to the UN's Sustainable Development Goals: Are they Adequate? By Clement A Tisdell, May 2019.
209. COVID-19: Trade-offs, Choices and Economics by Clem Tisdell, May 2020