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Analysis

Inter-district rice water productivity differences in Bangladesh: An empirical exploration and implications

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ABSTRACT

While the bulk of research on crop water productivity (WP) focuses on static cross-section analysis, this research provides a spatio-temporal perspective. It estimates rice crop WP for 21 Bangladesh districts for 37 years; explores WP variations among districts; and investigates causality involving WP, intensification and technological variables; and groundwater irrigation and depth. It breaks new grounds by probing these significant but unexplored issues.

Technological diffusion was the key factor explaining inter-district WP differences. The impact of agricultural intensification on *rabi* (dry season) and *kharif* (wet season) crop WPs was positive and negative respectively. Dummy variables typifying policy transition negatively impacted on WPs for both *kharif* and overall crops. While *rabi* and *kharif* rice WPs grew with time, overall crop WP recorded the strongest growth. *Rabi* and overall WPs were lower in salinity- and drought-prone districts covering 33% of Bangladesh's net cropped area (NCA). In 90% of Bangladesh's NCA districts, technological diffusion caused WP. Causality existed between groundwater irrigation and depth in 60% NCA. Despite significant potential to increase WP, increasing dependence on groundwater appears unsustainable. Widespread diffusion of HYVs in the *kharif* season, and development of salinity and drought-tolerant rice varieties could go a long way in sustaining rice WP.

1. Introduction and Background

Literature on agricultural development has long neglected the measurement and explanation of productivity of a fundamental and, in many cases limiting, input — water. This stands in sharp contrast to the voluminous research on land and labor productivity in agriculture. It has long been recognized that with a growing population in Bangladesh and a dwindling supply of arable land per capita, there is very little prospect for expanding food production by bringing in more land under cultivation. The only way forward is to augment the productivity per hectare of cultivated land. In their influential work, Hayami and Ruttan (1985) espoused internal land-augmentation as opposed to external land-augmentation as a way of overcoming severe constraints on the supply of arable land per capita. The former refers to a situation where qualitative improvement in land input takes place, for instance, through irrigation while the latter refers to a situation where cultivation is based on the extensive margin.

In the densely populated and land-scarce countries of South Asia, internal land augmentation has taken the form of increasing reliance on groundwater irrigation. In no other part of the world does people's livelihood depend so much on groundwater as it does in South Asia. As Shah (2007) reports, 55–60 and 60–65% of the respective populations in India and Pakistan depend on groundwater for their livelihoods. Given the high and increasing dependency on groundwater irrigation stated in Section 1.1, this figure for Bangladesh is likely to be at least as high as that of Pakistan. In contrast, the corresponding figure for China is in the 20–25% range.

First, the world pays more attention now than in the past to letting the market forces and the private sector operate. Many countries in the Third World (including Bangladesh) adopted structural reform programs, which were essentially institutional reforms that embodied a set of policies propelled by the IMF and the World Bank. These policies had the explicit aim of opening up the Third World countries to world market competition so as to: (1) promote their exports, and (2) restrain domestic expenditure in order to create a better climate for investment and enhance economic growth (Messkoub, 1992, p. 198). In many countries, structural adjustment policies permeate every aspect of the economy (Rahman, 1992).

Second, the depletion and degradation of land and water resources due to agricultural intensification seem amply clear. This is a global as well as a South Asian phenomenon (Alauddin and Hossain, 2001; Prescott–Allen, 2001; Shah, 2009). The adverse impact of intensive

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agriculture on soil quality in parts of Bangladesh is well documented (see, for example, Ali et al., 1997). In south-eastern Nigeria, farm-level data suggested that about nine percent of the soil in irrigated land has been degraded to the extent that it is no longer suitable for arable agriculture (Urama, 2005, p.199).

Therefore, the focus of technological innovations must shift from just land-augmentation to environment-saving by considering environment as factor of production (Alauddin, 2004; Alauddin and Quiggin, 2008). This paper focuses on the water-saving perspective of agricultural development, implying a higher crop yield/m^3 of water use (Barker and Levine, 2012, p.2).

The bulk of the research on crop water productivity (WP) available thus far has focused almost exclusively on static cross-sectional analyses. They have measured WP at different locations at a point of time precluding the possibility of examining any time trends. Ahmad et al. (2004) estimated rice and wheat WPs in the Rechna-Doab basin in the Pakistan Punjab. They employed remote sensing and Surface Energy-based Algorithm (SEBAL) modeling for evapotranspiration (ET) estimation. Cai and Sharma (2010) measured water productivity in the Indo-Gangetic basin using a range of methods including remote sensing, census and weather data. Mahajan et al. (2009) measured water productivity and yield of rice according to time of transplanting in the Indian Punjab. On the whole, measurement of water productivity as has been done by Ahmad et al. (2004) and Mahajan et al. (2009) is possible for a micro-level study. It is rather too laborious, cumbersome, and data-intensive to investigate crop water productivity for a larger geographical entity such as a country or regions within a country, let alone over time.

Vaidyanathan and Sivasubramaniyan (2004) measured changes in water demand for crop production for 13 Indian states between 1966–68 and 1991–93 employing consumptive water-use (CWU). CWU for a particular crop refers to the amount of water that a crop transpires during its course of growth and the amount of water that evaporates from the bare surface on which the crop grows (Amarasinghe et al., 2007; Vaidyanathan and Sivasubramaniyan, 2004).

CWU, as estimated by Vaidyanathan and Sivasubramaniyan (2004), used mean annual rainfall and ET; but this masked significant interregional and seasonal variations of rainfall within a state, and growth periods of crops. Amarasinghe et al. (2007) improved the Vaidyanathan and Sivasubramaniyan (2004) assessment of CWU in two important ways. First, they used average monthly rainfall and district-level ET. Second, they used crop coefficients (defined as the ratio of potential to actual ET, Pidwirny, 2006) corresponding to the four different periods of crop growth (initial, development, middle and late), and the crop calendar for different crops for four different regions to estimate CWU for India.

1.1. Overview of Changes in Bangladesh Agriculture

High yielding variety (HYV) rice has spearheaded the green revolution of the late 1960s in Bangladesh (Alauddin and Tisdell, 1991). Rice production consumes much more fresh water than any other crop of comparable value and duration (Allen et al., 1998; BARC, 2001). Almost all *rabi* (November–March) rice areas are currently allocated to HYVs while *kharif* (April–October) rice also has a significant component of HYVs for most districts. Bangladesh agriculture is characterized by the pre-eminent position of rice in its cropping pattern. Nearly 80% of the gross cropped area is allocated to rice (BBS, 2012).

Over time, Bangladesh has become increasingly dependent on groundwater irrigation for agricultural crop production. From next to nothing at the beginning of the green revolution in the late 1960s and early 1970s, groundwater is now the pre-eminent source of irrigation (BBS, 2012). However, there are significant inter-district variations. Fig. 1 illustrates the locations of the 64 (smaller) districts with their respective numbers.

Information contained in various issues of Yearbook of Agricultural Statistics of Bangladesh (BBS, 2008), suggests that the (greater) districts of Bogra (#8, 9), Dinajpur (#1–3), Jessore (#20–23), Kushtia (#17–19), Pabna (#14 and #16), Rajshahi (#11–13 and #15), and Rangpur (#4–7 and #10) located in the northern and western zones, and the (greater) districts of Jamalpur (#33 and #36), Mymensingh (#34 and #38), and Tangail (#37) in the central region are characterized by groundwater dependency of more than 85% of the gross irrigated area. The combined net cropped area (NCA) of these greater districts accounts for half of Bangladesh's total NCA. This phenomenon has drastically shifted the ground–surface water relativities in irrigation from almost nil to nearly all, in some cases. Three standout (greater) districts are Bogra, Tangail and Dinajpur with about 15% of Bangladesh's net cropped area, where groundwater irrigation is respectively 54, 34 and 24 times as important as surface water irrigation.

Increasing dependence on groundwater extraction has led to significant lowering of groundwater tables. The maximum groundwater depth is significantly positively correlated with the incidence of groundwater irrigation, as measured by the percentage of groundwater-irrigated area in gross area irrigated for almost all districts. This is especially so for the (greater) districts of Dhaka, Mymensingh, Tangail, Bogra, Pabna and Rajshahi, and Jessore and Kushtia.

Changes in the five yearly average maximum groundwater depths between the early 1970s and the early 2000s in selected regions of Bangladesh (CEGIS, see Section 3.1) suggest that Dhaka, which includes mostly the city area, has suffered the greatest increase in the maximum groundwater depth (by 42 m). This seems consistent with the finding that groundwater table in Bangladesh's capital city, Dhaka, has declined by an average of 1 m/year over the last three decades (Zahid and Ahmed, 2006, p.40). However, this phenomenon may not be entirely related to agricultural activities but due to a dramatic increase in Dhaka city's population from just under 1.68 million in 1974 (BBS, 1984, p.44) to 14.54 million in 2011 (http://www.citypopulation.de/php/bangladesh-dhaka.php).

Greater risk of drought combined with increasing extraction of groundwater resources can exacerbate the impact of drought on crop yield. Information limitations preclude the possibility of an in-depth analysis of the effect of drought on crop productivity. Karim and Iqbal (1997) provide an estimate of loss of crop yield of transplanted *aman* (*kharif*) rice due to drought in all three stages of the crop production process (panicle initiation, heading to milk, and milk to maturity) that approximately correspond to the 7th, 8–9th and 10–12th ten-day growth periods respectively in the present study. Karim and Iqbal (1997, p.75) further report that the impact of the loss is particularly severe during the milk-to-maturity stage.

There are also significant spatial variations to the effect of drought. Given the higher incidence of drought in the northern district of Rajshahi and western districts of Jessore and Kushtia, these are more adversely affected than the central district of Dhaka and the eastern districts of Comilla or Sylhet. Furthermore, the duration of the drought is much longer (13 days each) for Jessore and Rajshahi compared to eight and four days respectively for Comilla and Sylhet. Drought-stress-affected yield is only 43 and 38% respectively of the no-drought-stress yield. The eight (greater) districts (Barisal, Faridpur, Kushtia, Jessore, Khulna, Pabna, Patuakhali and Rajshahi), located in the Ganges basin (with about 38% Bangladesh's NCA) are characterized by high climatic variability. Some of these districts are susceptible to severe droughts while others are susceptible to salinity. This area is likely to experience even greater climatic variability in coming decades. By 2050, the dry season (November–May) water deficit will rise to 24.6% from 9.4% in 2025. On the other hand, the wet season (June–October) water surplus will increase to 29.7% from 8.85% over the same period (WARPO, 2002, p.13).

Bangladesh's public policy stance pertaining to agriculture, especially in relation to pricing of key agricultural inputs such as irrigation, chemical fertilizers and pesticides has changed significantly since the 1980s

Fig. 1. Map of Bangladesh showing the 21 districts with their 64 constituent units.
Source: Adapted from http://bdbccgroup.files.wordpress.com/2011/09/small_administrative_map_of_bangladesh.jpg; www.aitlbd.net/bangladesh/mapsbd/index.html).

and has resulted in the withdrawal of subsidies on them. Bangladesh has been pursuing a policy of initial transition to and subsequently a complete deregulation of the agricultural input market. These were done primarily on the basis of World Bank and IMF prescriptions under the structural adjustment program (Jahan et al., 1999; Shand and Alauddin, 1997).

This policy change led to an increase in the price of all agricultural inputs including agricultural machinery (shallow and deep tube wells, and low lift pumps) and chemical fertilizers reflecting their 'true' price. Furthermore, the policy makers also had to consider the highly porous border with India and a significantly lower fertilizer price in Bangladesh than in India that would always encourage illicit border trade (Hossain et al., 1997). This policy rationalization occurred in two discernible phases. The decade of the 1980s represents the initial phase of policy transition from a regulated policy regime to one based on a greater reliance on market forces. The period since the 1990s typifies the phase during which the economy has experienced the deepest penetration of market forces and highest degree of openness in the external sector (Hossain and Alauddin, 2005).

Against this background, the present study departs from the existing literature by using panel data to provide a spatio-temporal perspective (Cameron and Trivedi, 2010) and explore issues that have not been addressed before in WP analysis. This paper focuses on rice only, given its importance in Bangladesh agriculture. However, the methodological framework can be easily extended to other crops as well.

More specifically, the paper:

- estimates rice crop WP for 21 (greater) districts of Bangladesh covering a period of 37 years from 1968 to 2004;
- explores WP variations among districts according to several factors such as district location (e.g., in the salinity- or drought-prone areas), indicators of technological diffusion and agricultural intensification, and time trend or phases within the time series that typify extent of agricultural input pricing policy liberalization; and
- explores causality involving WP, agricultural intensification and technological diffusion. It also explores causality between groundwater irrigation and its depth.

Note that availability of data on all the necessary variables precluded the possibility of extending the time series beyond 2004 and carrying out analysis for 64 (smaller) districts instead of 21 (greater) districts.

The paper is organized as follows: Section 2 outlines the methodological framework, Section 3 analyzes the data, Section 4 presents the empirical results and Section 5 follows it up with a discussion and conclusions.

2. Methodological Issues

2.1. Measurement of Water Productivity

Measurement of water productivity entails significant methodological issues. This is because, it involves the use of both scientific and statistical information on a range of variables including water requirements for crops, precipitation and evapotranspiration, irrigation, crop calendar, crop output and related data. For a particular crop or a group of crops, WP is defined as a ratio of crop output to CWU.

Estimation of CWU is undertaken by employing Eq. (1) (Amarasinghe et al., 2007, p.7).

$$CWU_{\mathrm{l}} = \begin{cases} \sum\limits_{k\in\mathrm{seasons}} IRA_{\mathrm{lk}} \sum\limits_{j\in\mathrm{months}} \sum\limits_{i\in\mathrm{growth\ periods}} kc^{\mathrm{l}}_{\mathrm{ki}} \times ETp_{\mathrm{j}} \times \dfrac{d_{\mathrm{ij}}}{n_{\mathrm{j}}} & \text{for irrigated crops} \\ \sum\limits_{k\in\mathrm{seasons}} RFA_{\mathrm{lk}} \sum\limits_{j\in\mathrm{month}} \sum\limits_{i\in\mathrm{growth\ periods}} \min\left(kc^{\mathrm{l}}_{\mathrm{ki}} \times ETp_{\mathrm{j}}, Effrf_{\mathrm{j}}\right) \times \dfrac{d_{\mathrm{ij}}}{n_{\mathrm{j}}} & \text{for rain-fed crops} \end{cases} \tag{1}$$

where:

- IRA_{lk} and RFA_{lk} respectively represent irrigated and rain-fed areas of the *l*th crop in the *k*th season;
- *i* is the number of growth periods during a cropping season, generally four (initial, development, middle and late) but could be more (e.g., number of 10-day segments of the total growth period of the relevant crop);
- d_{ij} is the number of days of the *j*th month in the *i*th crop growth period;
- n_{j} is the number of days of the *j*th month;
- *kc* is the crop coefficient of the crop in the *i*th growth period of the *k*th season;
- $Effrf_{\mathrm{j}}$ is the effective rainfall for the period of the month in which the crop is grown.

Eq. (1) embodies two multipliers:

(a) For irrigated crops, it is simply the expression involving the second and the third summation signs and entails the use of crop ET ($=kc^{\mathrm{l}}_{\mathrm{kl}} \times ETP_{\mathrm{j}}$) on the assumption that irrigation meets the full water requirements of the crops. In reality, however, this may not always be the case. This is because in many water-scarce areas (or where farmers do not have full control over irrigation), irrigation may not meet the full water requirement. In the absence of any dependable information, the authors had no alternative but to assume away any deficit in irrigation water.

(b) For rain-fed crops, it is the minimum of (crop ET, $Effrf_{\mathrm{j}}$).

This study calls the multiplier (a) the irrigated multiplier (IM) and the multiplier (b) the rain-fed multiplier (RM). Based on Amarasinghe (2005, p.9), Eq. (2) estimates effective rainfall.

$$\begin{aligned} &Effrf = AMR * (1-0.25 * AMR)/125 \text{ if } AMR \leq 250 \text{ mm;} \\ &\text{or } Effrf = 125 + 0.1 * AMR \text{ if } AMR \geq 250 \text{ mm} \end{aligned} \tag{2}$$

where *Effrf* and *AMR* respectively represent millimeters of effective rainfall and average monthly rainfall.

2.2. Factor Analysis, Regression Model and Causal Relations

There might be many variables that influence the dimensions involving agricultural intensification and technological diffusion. It is not possible to include all of them as explanatory variables in the same model. Factor analysis provides an analytical framework to derive an orderly simplification of a relatively large number of variables to a small number of representative constructs that reflect the underlying phenomena. Thus, factor analysis brings together variables that belong to a similar group (Field, 2005; Tabachnick and Fidell, 2007).

For panel data, ordinary least squares (OLS) estimates are likely to be inappropriate due to the presence of heteroscedasticity and first-order autocorrelation. In view of the likely occurrence of these problems, the present study employs generalized least squares (GLS) estimates corrected for heteroscedasticity and first-order autocorrelation (Wooldridge, 2002).

While regression analysis can explore the dependence of WP on a number of variables, the existence of significant relationship does not necessarily imply that one causes the other or the direction of causality. However, in regressions using time series data, the scenario might be different (Gujarati, 2003). Given that, in the present study the estimated WPs, agricultural intensification and technological diffusion have time dimension, it is useful to explore any causal relationship involving these variables employing Granger causality tests (Granger, 1969). Furthermore, in view of the phenomenal increase in groundwater usage and its likely impact on groundwater table, it is worth exploring any causal relation between the two variables. This is undertaken in Section 4.3.

3. Data

The data used in this study warrant some discussion as they came from various scattered sources and required further processing for the derivation of water productivity measures. The remainder of this section is devoted to it.

3.1. Components of Panel Data

Data for 21 districts for 37 years (except for three districts — Jamalpur (27 years), Patuakhali (36 years) and Tangail (36 years)) spanning the period of 1968–2004 on crop area, production, irrigated area, crop area allocated to HYVs, and land utilization (total land area, net and gross areas cultivated, and cropping intensity), were compiled from those reported in the various issues of Yearbook of Agricultural Statistics of Bangladesh published by the Bangladesh Bureau of Statistics.

Data on monthly rainfall and mean groundwater depth available for 64 (smaller) districts were procured by the authors from Water Resource Planning Organization (WARPO, www.warpo.gov.bd) and Centre for Environmental and Geographical Information System (CEGIS, http://www.cegisbd.com/). Note that WARPO and CEGIS collect and store relevant data from various agencies e.g., Bangladesh Water Development Board. For most districts, the information was available until 2002. The present study extended the series to 2004 by using the median values of the preceding five years.

Rice crops did not have any separate production and yield data of the rain-fed and irrigated ecosystems on a time series basis. The only data available to the authors were from Flood Plan Coordination Organization (FPCO, 1991). These have been used to derive separate crop production estimates. While this was not entirely satisfactory, the authors had little choice but to use them while acknowledging their limitations.

3.2. Components of Non-panel Data

Monthly ET data for the 64 districts were purchased from CEGIS. These data are invariant with time but have spatial dimensions.

Data on crop coefficients were available on a decadal (ten-day) basis for different crops of rice and their median sowing/transplanting and harvesting periods were procured from CEGIS. They represent one set of numbers for each crop corresponding to the relevant ten-day growth period. This contrasts with the data of Amarasinghe et al. (2007), which considered only four growth periods of a crop. In reality, however, a rice crop may have as many as 10–12 ten-day growth periods, each with different coefficients. The approach of the present study provides a greater degree of disaggregation than would have been the case with only four growth periods used by Amarasinghe et al. (2007).

The ET and monthly rainfall data available for the 64 (smaller) districts were reduced to the 21-district level in order to conform to the crop production and related data by averaging the information for the constituent districts, as illustrated in Fig. 1.

Table 1
Descriptive statistics of water productivity (WP), Bangladesh districts, 1968–2004.
Source: Based on data from Bangladesh Agricultural Research Council (BARC, 2001); various issues of Yearbook of Agricultural Statistics of Bangladesh; Water Resource Planning Organization (WARPO) and Centre for Environmental and Geographical Information System (CEGIS).

21 Greater districts (smaller districts in Fig. 1)	Rice WP (kg/m^3 of CWU)			Difference in *rabi* rice WP (%) over		Coefficient of variation (%)		
	Kharif	*Rabi*	Overall	*Kharif*	Overall	*Kharif*	*Rabi*	Overall
Barisal (#24, 28–30)	0.287	0.471	0.306	64.1	53.9	19.3	13.6	18.4
Bogra (#8–9)	0.387	0.481	0.412	24.3	16.7	25.1	24.5	26.8
Chittagong Hill Tracts (#61–62, 64)	0.423	0.421	0.422	−0.5	−0.2	23.5	11.3	19.7
Chittagong (#60, 63)	0.470	0.451	0.459	−4.0	−1.7	22.9	11.1	16.0
Comilla (#54–56)	0.358	0.522	0.407	45.8	28.3	22.5	22.5	22.5
Dhaka (#39–44)	0.293	0.472	0.367	61.1	28.6	23.9	17.2	25.1
Dinajpur (#1–3)	0.347	0.509	0.367	46.7	38.7	18.3	12.8	22.0
Faridpur (#45–49)	0.216	0.516	0.280	138.9	84.3	24.2	17.2	34.6
Jamalpur (#33, 36)	0.320	0.480	0.371	50.0	29.4	20.8	16.3	21.1
Jessore (#20–23)	0.347	0.459	0.358	32.3	28.2	36.9	14.1	35.0
Khulna (#25–27)	0.343	0.355	0.344	3.5	3.2	28.1	20.1	25.9
Kishoreganj (#35)	0.348	0.447	0.400	28.4	11.8	25.1	20.0	22.4
Kushtia (#17–19)	0.314	0.424	0.325	35.0	30.5	33.7	22.3	36.1
Mymensingh (#34, 38)	0.331	0.438	0.362	32.3	21.0	21.6	24.4	24.2
Noakhali (#57–59)	0.328	0.481	0.357	46.6	34.7	22.8	16.0	21.7
Pabna (#14, 16)	0.275	0.493	0.335	79.3	47.2	33.7	17.8	35.5
Patuakhali (#31–32)	0.290	0.382	0.297	31.7	28.6	23.0	27.5	19.7
Rajshahi (#11–13, 15)	0.336	0.437	0.358	30.1	22.1	31.3	24.9	31.4
Rangpur (#4–7, 10)	0.362	0.472	0.381	30.4	23.9	24.6	17.8	26.1
Sylhet (#50–53)	0.339	0.344	0.342	1.5	0.6	20.5	21.3	19.7
Tangail (#37)	0.293	0.570	0.378	94.5	50.8	24.7	14.1	27.3

Note: These are estimated using Eq. (1) above and averaged by the number of years for each district. Figures in columns 5–6 are derived as (column 3 / column 2) ∗ 100 − 100 and as (column 4 / column 2) ∗ 100 − 100 respectively. Columns 7–9 = (std. dev of water productivity for a district / corresponding figure in columns 2–4) ∗ 100.

4. Results

4.1. Descriptive Statistics: An Interpretive Overview

Table 1 presents the descriptive statistics of water productivity measures by rice crops and districts for the 1968–2004 period. These are estimated using Eq. (1) above.

Thus, each figure presented in columns 2–4 represents a 37-year average for the corresponding district except for Jamalpur (27 years), Patuakhali (36 years) and Tangail (36 years). Columns 5 and 6 represent, respectively, the percentage differences in *rabi* rice water productivity over those for *kharif* and overall (weighted average *kharif* and *rabi*) crops. Inter-district comparison of variability in water productivity requires the use of relative (coefficient of variation in columns 7–9) rather than absolute variability (standard deviation).

Rabi rice WP is considerably higher than those of both *kharif* and overall crops for all but four districts (Chittagong, Chittagong Hill Tracts, Khulna and Sylhet). For these districts, *rabi* rice WP is just below or above the ones for the other rice crops. For six districts (Dhaka, Faridpur, Jamalpur, Pabna and Tangail) *rabi* rice WP is higher than *kharif* and overall rice WP by at least 50%. As can be seen from the last three columns of Table 1, *kharif* and overall rice water productivity for most districts is more variable than those for the *rabi* crop except for the four districts mentioned above. This may be due to the fact that whereas the *kharif* rice mainly depends on the variable nature of the rainfall, the *rabi* crop is irrigated with a more dependable groundwater source.

4.2. Exploring District-level Water Productivity Differences

A range of variables is likely to affect water productivity measures. These may represent such dimensions as technological change, or those that may have contributed to the process of agricultural intensification. There might also be other variables that are discussed in Section 4.2.2.

4.2.1. Indicators of Agricultural Intensification and Technological Diffusion: Factor Analysis

The present factor analysis initially considered a total of 16 variables to derive a small number of representative dimensions (factors). However, for the sake of interpretation and keeping the factors to a manageable number, five variables had to be excluded from the final factor analysis because their inclusion neither increased the percentage of variance explained (i.e., total variance of all the variables included), nor did they produce a factor loading greater than 0.400. Furthermore, their exclusion improved internal consistency of the extracted factors. This is consistent with the conventional practice as researchers take the loading of an absolute value above 0.300 to be important (Field, 2005). The present study applies a more conservative threshold of a factor loading greater than 0.400. Note that factor loadings represent the correlation between the factor and the original variables and are critically important in understanding the nature of a particular factor (Hair et al., 2010). The five excluded variables were:

1. Mean groundwater depth;
2. Ratio of groundwater irrigated area to surface-water irrigated area;
3. Useable recharge;
4. Surface water as a percentage of total irrigated area; and
5. Non-rice crop as a percentage of total cropped area.

The number of variables included and the number of factors extracted were decided on the basis of percentage of variance explained by the extracted factors and their internal consistency. The two factors (Table 2) explained 69.3% of the total variance (Factor 1, 48.9%, and Factor 2, 20.4%). The explanatory power of the model was deemed satisfactory, given that extraction of a higher number of factors did not lead to any increase in the explanatory power. Cronbach's α (measuring internal consistency) was calculated using the variables defining Factor 1 and Factor 2. The α-values were 0.876, and 0.847 respectively. These met the threshold value of 0.70 for internal consistency for all variables defining each factor. Note that factors represent the linear combination of the original variables and the underlying dimensions that account for the original set of observed variables (Hair et al., 2010). Table 2 reports the results of factor analysis.

Table 2
Two factors reflecting agricultural intensification and technological diffusion in Bangladesh agriculture.

Description	Factor loading
Factor 1: Agricultural intensification [intensification]	
Rabi season rice and wheat area irrigated as a percentage of gross area irrigated	0.871
Net agriculture intensity (net cropped area i.e., excluding multiple cropping as a percentage of total land area)	0.834
Gross agriculture intensity (gross cropped area gross cropped area i.e., including multiple cropping as a percentage of total land area)	0.781
Cropping intensity (gross cropped area i.e., including multiple cropping as a percentage of net cropped area)	0.764
Crop concentration ratio (gross rice area as a percentage of gross cropped area)	0.764
Rice area irrigated as a percentage of gross area irrigated	0.763
Rabi rice area irrigated as a percentage of gross area irrigated	0.503
Factor 2: Technological diffusion [diffusion]	
Percentage of high yielding variety (HYV) in all rice area i.e., including multiple cropping	0.977
Percentage of high yielding variety (HYV) area in total *kharif* rice area	0.937
Percentage of high yielding variety (HYV) area in total *rabi* rice area	0.715
Groundwater irrigation as percentage of total irrigated area	0.621

Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.

The seven variables under Factor 1 epitomize the process of agricultural intensification. Broadly speaking, three types of variables underlie this dimension (Table 2). Variables 1, 6, and 8 relate to groundwater irrigation. Variables 2, 3 and 4 relate to agriculture intensity of the Bangladesh economy, while Variable 5 represents rice intensity of the crop sector of Bangladesh.

The four variables underlying Factor 2 underscore the process of technology diffusion. Three variables including percentage of high-yielding variety of rice in all-rice area (Variables 8–10 in Table 2) and groundwater irrigation as a percentage of total irrigated area (Variable 11 in Table 2) define this construct.

4.2.2. Exploring Water Productivity Differences Among Districts: Generalized Least Squares Results

Now, the paper explores the differences in WP levels among districts, and over time. In doing so, it uses the two factors (agricultural intensification and technological diffusion) that were extracted earlier as explanatory variables. The list of possible explanatory variables is expanded by including the following:

Time: Time trend, 1968 = 1, and so on.

Policy transition 1: 1 if the data relate to the 1981–90 (inclusive) period, 0 otherwise. This represents the initial phase of policy transition from a regulated policy regime to one based on greater reliance of the market forces.

Policy transition 2: 1 if the data related to the 1991–2004 (inclusive) period, 0 otherwise. This is the phase in which the economy experienced the deepest penetration of market forces and highest degree of openness to external trade.

Salinity prone area: 1 if the data corresponded to the (greater) districts of Barisal (#24, 28–30), Khulna (#25–27), and Patuakhali (#31–32), 0 otherwise.

Table 3
Explanation of inter-district rice water productivity differences: Generalized least squares estimates after accounting for heteroscedasticity and first-order autocorrelation.

Explanatory variable	*Kharif* crop		*Rabi* crop		Overall crop	
	Coefficient	*p*-Value	Coefficient	*p*-Value	Coefficient	*p*-Value
Agricultural intensification	−0.010	0.000	0.020	0.000	−0.003	0.081
Technological diffusion	0.069	0.000	0.033	0.000	0.064	0.000
Policy transition 1	−0.050	0.000	−0.006	0.601	−0.044	0.000
Policy transition 2	−0.061	0.000	0.018	0.376	−0.048	0.000
Salinity prone area	0.001	0.200	−0.032	0.002	−0.015	0.005
Drought prone area	−0.004	0.502	−0.021	0.014	−0.022	0.000
Time trend	0.004	0.000	0.002	0.085	0.005	0.000
Intercept	0.296	0.000	0.427	0.000	0.305	0.000
N	764	–	764	–	764	–
Wald test $\chi^2(7)$	1771.69	0.000	383.20	0.000	3520.68	0.000

Drought prone area: 1 if the data related to (greater) districts of Jessore (#20–23), Kushtia (#17–19) and Rajshahi (#11–13, 15).

GLS estimates are presented separately for *kharif*, *rabi* and overall rice crops in Table 3. Technological diffusion consistently outperformed any other variables explaining water productivity differences. While its effects are significantly positive for water productivity of all rice crops, the coefficients for the *kharif* and overall crops are twice as large as the one for the *rabi* crop. The process of technological diffusion is propelled by groundwater irrigation.

Agricultural intensification had a significantly positive effect on the *rabi* crop and a significantly negative effect on the *kharif* crop. For the overall crop, the coefficient of this variable is negative and significant only at the 10% level.

Both policy transition variables had significant negative effects on the *kharif* and overall crops. While WPs for all crops of rice grew with time, the one for the overall rice crop was 5 g per year. *Kharif* WP grew by 4 g annually while *rabi* WP recorded a growth of 2 g. To put it in context, ceteris paribus at the end of the time series, WPs for *kharif*, *rabi* and overall crops of rice would have increased by 148, 74 and 185 g from their respective levels in 1968. It should, however, be noted that the growth of *rabi* WP was from higher base values compared to the other two crops as indicated by the average for the entire period presented in Table 1.

Rabi and overall rice WPs are significantly lower in the salinity- and drought-prone districts. This is not unexpected, given that Bangladesh is yet to make a significant progress in developing salinity- and drought-tolerant varieties of rice (BRRI, 2011).

4.3. Exploring Causal Relationships

Granger causality tests did not find any evidence of two-way causation. Results presented in Table 4 represent one-way causality running from agricultural intensification and technological diffusion to the respective rice crop WPs. A contrasting picture emerges with respect to agricultural intensification and technological diffusion.

For only three districts accounting for about 10% of Bangladesh's NCA, agricultural intensification *caused* rice water productivity of *kharif*, *rabi* and overall rice crops. On the contrary, technological diffusion was a casual factor in the case of rice WPs of *kharif*, *rabi* and overall crops for most districts covering 90% of Bangladesh's NCA.

At this stage, it is also important to explore any causal relationship between mean groundwater level and area irrigated from groundwater sources as a percentage of total area irrigated. It is plausible

Table 4
Results of Granger causality tests: Rice WP vis-à-vis agricultural intensification and technological diffusion.

21 Greater districts (smaller districts in Fig. 1)	Causality running to *kharif* rice WP from		Causality running to *rabi* rice WP from		Causality running to overall rice WP from	
	Intensification	Diffusion	Intensification	Diffusion	Intensification	Diffusion
Barisal (#24, 28–30)	√**	√***	√***	X	√***	√**
Bogra (#8–9)	X	√***	X	√***	X	√***
Chittagong Hill Tracts (#61–62, 64)	X	√**	X	X	X	√*
Chittagong (#60, 63)	√*	√***	X	√*	√*	√***
Comilla (#54–56)	X	√***	X	√**	X	√***
Dhaka (#39–44)	X	√*	X	√*	X	√**
Dinajpur (#1–3)	X	√***	X	√***	X	√***
Faridpur (#45–49)	X	√***	X	√***	X	√***
Jamalpur (#33, 36)	X	√***	X	X	X	√**
Jessore (#20–23)	X	√***	X	√**	X	√**
Khulna (#25–27)	X	√***	X	√***	X	√***
Kishoreganj (#35)	X	√***	X	√***	X	√***
Kushtia (#17–19)	X	√***	X	√***	X	√***
Mymensingh (#34, 38)	X	√**	X	√**	X	√*
Noakhali (#57–59)	X	√*	√***	X	X	X
Pabna (#14, 16)	X	√***	X	√***	X	√***
Patuakhali (#31–32)	X	X	X	X	X	X
Rajshahi (#11–13, 15)	X	√***	X	√***	X	√***
Rangpur (#4–7, 10)	X	√***	X	√***	X	√***
Sylhet (#50–53)	X	√***	X	√***	X	√***
Tangail (#37)	√**	√**	X	√**	X	√**

Note: √***, √** and √* respectively imply that the null hypothesis of no causality can be rejected at 1, 5 and 10% levels of significance respectively and with a one period lag. X implies absence of any causal relationship.

Table 5
Results of Granger causality tests between groundwater as a percentage of total area irrigated causes mean groundwater depth.

21 Greater districts (smaller districts in Fig. 1)	Groundwater as a % of total area irrigated *causes* mean groundwater depth	Mean groundwater depth *causes* groundwater as a % of total area irrigated	Direction of causality
Barisal (#24, 28–30)	X	X	–
Bogra (#8–9)	√***	√***	Two-way
Chittagong Hill Tracts (#61–62, 64)	X	X	–
Chittagong (#60, 63)	X	X	–
Comilla (#54–56)	X	X	–
Dhaka (#39–44)	√***	√**	Two-way
Dinajpur (#1–3)	X	X	–
Faridpur (#45–48)	√***	√**	Two-way
Jamalpur (#33, 36)	√**	X	One-way
Jessore (#20–23)	X	X	–
Khulna (#25–27)	X	X	–
Kishoreganj (#35)	√**	√***	Two-way
Kushtia (#17–19)	√***	√**	Two-way
Mymensingh (#34, 38)	√**	√**	Two-way
Noakhali (#57–59)	X	X	–
Pabna (#14, 16)	√***	√***	Two-way
Patuakhali (#31–32)	X	X	–
Rajshahi (#11–13, 15)	√***	√***	Two-way
Rangpur (#4–7, 10)	X	√***\	One-way
Sylhet (#50–53)	√***	√***	Two-way
Tangail (#37)	√***	√***	Two-way

Note: √***, and √** respectively imply that the null hypothesis of no causality can be rejected at 1 and 5% levels of significance with a one period lag implying a causal relationship. X denotes absence of any causality.

that increased abstraction of groundwater resources lead to depletion of groundwater tables in the absence of full recharge of aquifers (Shamsudduha et al., 2011). It is also possible that depleting groundwater tables might lead to greater usage of groundwater in the face of dwindling surface water sources. Table 5 presents the results of causality tests.

Ten districts with about half of Bangladesh's NCA of the 21 districts show a two-way causation between mean groundwater depth and percentage of total area irrigated from groundwater sources. Two districts, Rangpur and Jamalpur with 11% of the country NCA, show one-way causation but in opposite directions. For Jamalpur with only about 3% of the country NCA, percentage of total area irrigated from groundwater sources *causes* mean groundwater depth. On the other hand, for Rangpur with 8% of Bangladesh's NCA, mean groundwater depth *causes* percentage of total area irrigated from groundwater sources.

5. Discussion and Conclusions

Overall rice water productivity in Bangladesh is relatively low (0.306–0.459 kg/m^3 of CWU) both by South Asian and international standards. It is also characterized by significant variation across districts. This stands in sharp contrast to rice WP in parts of India at 1.540 kg (Singh et al., 2006), 1.250–1.510 kg (Mahajan et al., 2009), and 0.570–1.180 kg (Cai and Sharma, 2010) and by global standards of 0.600–1.600 kg (Zwart and Bastiaanssen, 2004). This implies very low levels of water productivity offering a significant scope for improvement.

Spread of HYVs is a key determinant of rice water productivity. However, the spread of this technology in the dry season depends critically on the access to irrigation, more specifically groundwater resources.

This notwithstanding, widespread diffusion of HYVs during *kharif* season is yet to occur. This is due to greater risks and uncertainty due to variable weather conditions. Technological breakthroughs are yet to take a firmer root to circumvent these uncertainties. Salinity and drought prone areas require rice varieties that are yet to experience significant scientific breakthroughs.

One implication for the increasing incidence of rice cultivation is that the process of agricultural production has become more water dependent. In the dry season, rice and pulses are competing crops. The former is at least one and half times more water-intensive than pulses. Furthermore, the growing season for pulses is considerably shorter than for rice (BARC, 2001, p.116). Why then farmers allocate more land to *rabi* rice than pulses? There are two likely reasons for this. First, technological progress in pulses has lagged far behind that in rice. Second and more importantly, rice is the staple food and gives a high and stable yield during *rabi* season. Therefore, bringing the agricultural input prices to their scarcity value in itself might not have resulted in the adverse effect on *rabi* rice water productivity.

However, the problem lays elsewhere. While few would disagree with such a policy rationalization, what was really lacking was a proper institutional arrangement underlying the supply and distribution of different inputs that were essential for irrigation. Uncertainty and disruption in the diesel and power supply for irrigation are quite common. *Rabi* HYVs of rice are completely dependent on irrigation and timely application of complementary inputs such as chemical fertilizers. Given that the dry season evapotranspiration exceeds precipitation in most districts but especially in the drier districts, adequacy and timely availability of key inputs is critically important. Usually this is the case in the dry season.

However, rice cultivation under rain-fed conditions as is the case during the *kharif* season provides a different scenario in that there is considerable uncertainty with the timeliness and adequacy of rainfall. Furthermore, high input costs relative to return may militate against using supplementary irrigation. This could be the underlying reason for the significant negative signs of the two policy regime dummy variables on the *kharif* rice WP.

It is debatable whether the present water productivity growth process is sustainable. Shah (2009) casts doubt about the sustainability of groundwater irrigation in South Asia. Similar concerns have been expressed in research from other parts of the world (see, for example, Urama, 2005).

This paper has provided a spatio-temporal perspective of rice productivity analysis in contrast to the received literature almost exclusively dominated by research focusing on static cross-section analysis. Issues taken up for specific investigation include: (a) estimation rice water productivity for 21 districts over 37 years; (b) an explanation of WP differences among districts; and (c) an exploration of casual relationships involving WP on the one hand and agricultural intensification and technological diffusion on the other; and between groundwater irrigation and depth of groundwater table. This present study has broken new grounds by exploring these issues which have not been explored in the existing literature. Even though developed as a case study of Bangladesh, the findings are likely to be of relevance to developing countries where similar conditions apply and data are available. Bangladesh's situation may not be unique in the world. For instance, many LDCs are confronted with the problems of dwindling supply of arable land per capita, and intense pressure on land. Its excessive reliance on groundwater has parallels with parts of other South Asian countries and this makes its case of additional interest.

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