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Water for Food in Bangladesh: Outlook to 2030

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International Water Management Institute

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Front cover photograph shows farmers planting Iri-Boro seeds, a well-known variety of paddy. Farmers work in the field despite the freezing cold in northern Bangladesh to recover the damages caused by two floods last year. Bogra, Bangladesh. January 30, 2008 (*photo:* Shafiqul Islam Shafiq/Majority World).

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Project

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Contents

Summary

This study assesses the changing consumption patterns of rice in Bangladesh and its implications on water demand by 2030. Rice dominates food and water consumption patterns in the country; it contributed to 72% of the total calorie supply from food, and 81% and 79% of the total cropped and irrigated area, respectively, in 2010. Forecasts using time series models show rice demand for food consumption, which was 172 kg/person/year in 2008, will have a negligible increase by 2 kg/person by 2030. The demand for rice for feed will double with increasing animal products in the diet, which is only 4% of the calorie intake in 2008. Between 2000 and 2010, the total population and demand for rice have increased by 15% and 22%, and these will increase further by 22% and 25%, respectively, over the next two decades. Forecasts of rice yield, area and production show that the country can meet the increasing demand for rice and can also have substantial production surpluses. However, the rice surpluses will come at a considerable environmental cost, because the demand for groundwater consumptive water use from irrigation alone could exceed the natural recharge in many locations. Bangladesh can mitigate potential water crises by limiting rice production to meet the requirements of self-sufficiency. Increases in water productivity of both *Aman* (wet season) and *Boro* (dry season) rice production can help too. A carefully designed deficit irrigation regime for *Boro* rice can increase transpiration, yield, water productivity and production, and reduce the pressure on scarce groundwater resources. Simultaneously, attention must also be given to exploring the potential of recharging groundwater using the vast amount of monsoon floodwaters to alleviate the stress on groundwater resources.

Water for Food in Bangladesh: Outlook to 2030

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Introduction

Food consumption patterns influence agricultural water demand of developing countries (Renault and Wallender 2000; Amarasinghe et al. 2007a; Hoekstra and Chapagain 2007; Liu and Savenije 2008; Liu et al. 2010). However, due to the large population and economic growth in Bangladesh, changes in food consumption patterns and water use, and their interactions are not clear. Rice is still the staple food. However, the consumption of animal products and vegetables has been increasing (Pingali 2007; Cirera and Masset 2010; Hossain 2010; Mukherjee et al. 2011). This increases the demand for commercial feed due to the scarcity of pastureland. This paper assesses the water demand for food and feed requirements in Bangladesh for the projected population to 2030, taking into consideration changing consumption patterns.

Meeting water demand for food, nutritional, livelihood and environmental securities in Bangladesh are significant challenges for the following reasons:

- The country has a large population: 152 million people in 2011 (BBS 2012) and another 30 million more by 2030 (UN 2011). Thus, achieving food security for all these people will be a huge a challenge (Faisal and Parveen 2004).

- The country had an exceptionally high population density of 964/km^2 in 2011 (GoB 2014), which is the highest among the developing countries in Asia. It also has one of the lowest landholdings of 0.6 ha/farm (BBS 2010a). As a result, the pressure on land is immense, often with detrimental implications on productivity (Rahman 2010; Rahman and Rahman 2009).

- The country has a large rural population that is dependent on agriculture; 70% of the population lives in rural areas and 40% are dependent on agriculture for their livelihoods; and many grow rice (BBS 2010a). Thus, ensuring there is sufficient water for the cultivation of rice is critical.

- Poverty levels are still very high; in 2010, 43% of the population were living below the international poverty line (USD 1.25/day) (World Bank 2013), and 31.5% of the population were living below the national poverty line (per capita calorie intake is less than 2,122 kilocalories [kcal] per day) (BBS 2010b). Achieving the nutritional and livelihood security of the poor is a huge challenge.

- The extreme climatic events, which are a recurrent phenomenon, affect a large part of the country, agriculture and the economy (Lal 2011; Yu et al. 2010; Sarker et al. 2012). The changing demand for rice will have implications on irrigation water demand. Rice directly contributes to 70% of the current calorie intake (FAO 2013a) and is the main cereal used for feeding animals. Rice production accounts for most of the cropped area (FAO 2013b). The irrigated rice area is gradually increasing; it was 26% of the total irrigated area in 1990 and increased to 45% in 2010 (BRRI 2013), and is likely to increase further in the future. Similarly, irrigation demand for other crops is also increasing, and so is the demand from other sectors (Chowdhury 2010). As a result, competition amongst these various users for a developed water supply will increase in the future.

The main objective of this paper is to estimate the water demand for future food and feed production in Bangladesh. The second section provides an overview of the food and water supply of the country, and the methodology used for estimating water demand. The analytical technique, Autoregressive Integrated Moving Average (ARIMA) time series, is used to forecast the demand for food, feed and other uses. The ARIMA model makes use of time series data between 1961 and 2012 to understand the changes in the recent past as accurately as possible, and then extrapolate the trends to the future in a "Business as Usual" scenario. The third section estimates food demand, and the fourth section estimates food supply. The fifth section estimates water demand for food and feed production under alternative water management scenarios of water productivity growth. The CROPWAT decision support tool developed by the Food and Agriculture Organization of the United Nations (FAO) is used to estimate the water demand for crops. The final section concludes the paper by making policy recommendations to meet the emerging challenges.

Methodology and Data

Overview of Food and Water Supply

Rice production, which is the major livelihood of the large rural population, increased threefold since the early 1970s (Table 1), but the rice area only increased by 18%. Irrigation is a major contributor to the increases in yield and production. Net irrigated area (NIA) has quadrupled over the last four decades and groundwater contributed 88% to this increase. However, the expansion of groundwater irrigation is already an environmental concern in some regions.

According to some studies (Zahid and Ahmed 2006; Shamsudduha et al. 2009; Shahid 2011; Ali et al. 2012), groundwater use is unsustainable in many regions; the depth to groundwater is

TABLE 1. Rice production and water-use patterns.

Factor	Units	1968-1972	1988-1992	2008-2012
Population	Millions	69	110	152
Rural population (% of total population)	%	92	79	71
Rice area	Mha	9.8	10.3	11.5
Rice production	MMt	17	26	49
Rice yield	t/ha	1.7	2.5	4.3
Net irrigated area (NIA)	Mha	1.2	2.7	5.1
Groundwater NIA	Mha	0.6	1.8	4.0
Rice irrigated area	Mha	1.1	2.5	4.3
Total renewable water resources (TRWR)	Bm^3	-	-	1,277
External renewable water resources (ERWR)	Bm^3	-	-	1,122
Internal renewable water resources (IRWR)	Bm^3	-	-	105
IRWR from groundwater	Bm^3	-	-	84
IRWR from surface water	Bm^3	-	-	21
Total water withdrawals	Bm^3	-	-	36
Groundwater withdrawals	Bm^3	-	-	28
Irrigation withdrawals	Bm^3	-	-	32

Sources: All data: FAO 2013d; rice production and net irrigated area: FAO 2013c.

Notes: Mha – million hectares, MMt – million metric tonnes, t/ha – tonnes per hectare, Bm^3 – billion cubic meters.

declining by 0.5 to 1.0 meter/year in northwestern, north-central and southwestern regions. Also, these areas are faced with widespread arsenic contamination (BGS and DPHE 2001) and related issues in rice production (Panaullah et al. 2009; Ahmed et al. 2011).

Yet, in 2008, the estimated total water withdrawals were only 3% of TRWR (1,277 Bm^3) (Table 1). Groundwater withdrawals, which are 80% of total water withdrawals, are one-third of IRWR from groundwater. Given that groundwater NIA has more than doubled in the last two decades, and that population growth is still high in rural areas, it is likely that the total demand for groundwater will increase even faster in the future. However, what is not clear from the above water-use patterns is how efficiently Bangladesh uses its water in the reservoirs, where the storage capacity stood at 20 Bm^3 by 1991 (FAO 2013d).

Methodology Used for Estimation of Food and Water Demand

Figure 1 shows the framework used to estimate future crop and water demand. The factors stated on the left side of the flowchart are the inputs used for estimation and prediction, and those on the right side are the outputs.

The eight steps of the framework are explained below:

Step 1 predicts the calorie intake of different crop commodities. The ARIMA time series models (Box and Jenkins 1976) forecast the per capita gross domestic product (GDP) and calorie intake to 2020 and 2030. The ARIMA (p, d, q) model has p and q autoregressive and moving average terms of the stationary time series of order d; it takes the form:

$$(Y_t - \alpha_1 Y_{t-1} - \alpha_2 Y_{t-2} - \cdots - \alpha_p Y_{t-p}) = \beta_0 + (u_t - \beta_1 u_{t-1} - \beta_2 u_{t-2} - \cdots - \beta_q u_{t-q}) \quad (1)$$

where: Y_t is the d^{th} difference[1] of the original time series, and u_t is a random noise. Differencing of the original variable gives a stationary time series.

The GDP per capita is the leading indicator for predicting the per capita calorie supply. The ARIMA models forecast the calorie demand of cereals and its major components rice and wheat, other products (including pulses, vegetable oils, fruits, vegetables and sugar) and animal products. The total calorie demand is the product of per capita calorie demand and population projections. This analysis uses the United Nations medium-variant population projections of the 2010 revision (UN 2011).

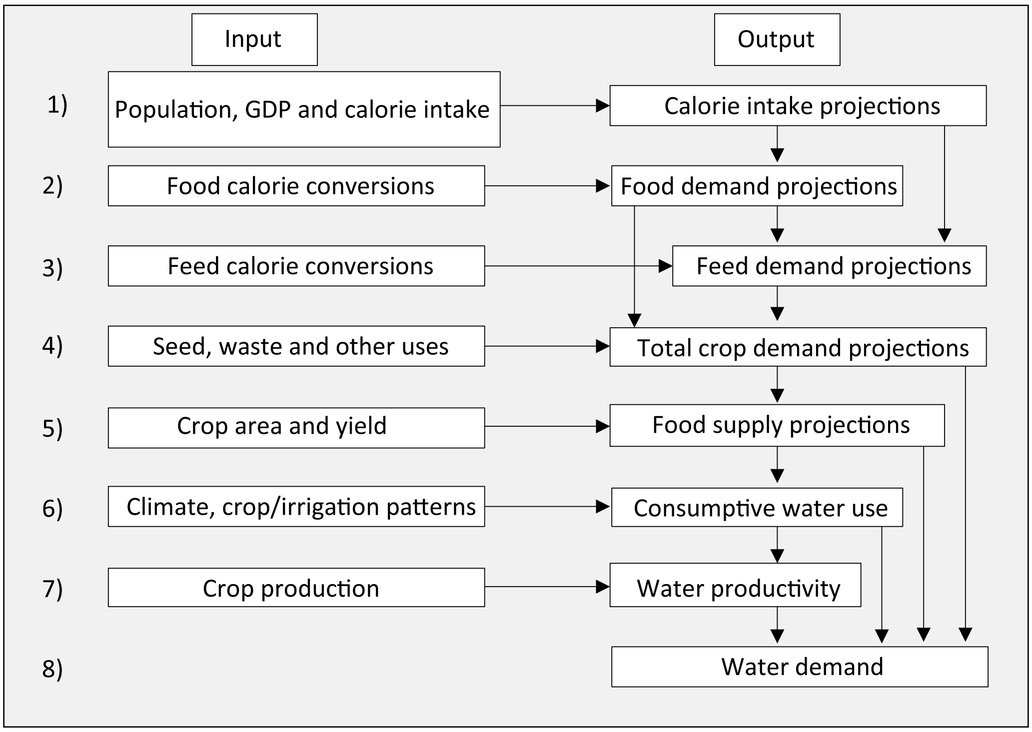
Step 2 estimates the food demand; it is the product of calorie supply from food and the food to calorie conversion ratio. The food to calorie conversion ratio (grams/kcal) is the quantity of food required to provide one kcal of nutritional supply. For rice, it is about 0.28 grams/kcal. The analysis uses the average of the food to calorie conversion ratios of the three most recent years where data are available.

Step 3 estimates the feed demand; it is the product of calorie supply from animal products and the feed to calorie conversion ratio. The feed to calorie conversion ratio of a crop is the ratio of the total quantity of crops/products used as feed to the calorie supply from animal products. The feed demand of cereals increases with increasing supply of animal products (Bradford 1999; Bhalla and Hazell 1997). This paper uses the past trends to project the future conversion ratios.

Step 4 estimates the total crop demand; it is the sum of the demand for food, feed, seed, and other uses and waste. The trend of the ratio of all uses (seed + other uses + waste) to total domestic supply indicates the patterns of seed, waste and other uses. The total crop demand is the ratio of total food and feed demand to the ratio of seed, waste and other uses, i.e., total crop demand = (food and feed demand)/(1 - (ratio of seed + other uses + waste)).

[1] For instance, the 1st difference is $\Delta Y_t = Y_t - Y_{t-1}$; and the 2nd difference $\Delta^2 Y_y = \Delta(Y_t - Y_{t-1}) = Y_t - 2Y_{t-1} + Y_{t-2}$, etc.

FIGURE 1. Framework used for estimating future crop and water demand.



Step 5 estimates the food supply. The ARIMA models predict the area and yield of rice production. The models project the rice supply separately for the three main seasons: *Aus* (pre-monsoon, equivalent to the pre-*Kharif* season in India), *Aman* (monsoon – equivalent to the *Kharif*) and *Boro* (dry season – equivalent to the *Rabi* season in India). Crops cultivated in the *Aus* (April to July) and *Aman* (June to November) seasons are generally rainfed, while crops cultivated in the *Boro* (December to May) season are mainly irrigated.

Step 6 estimates the consumptive water use (CWU) of different crops in the rainfed and irrigated areas. CWU is the evapotranspiration (ET) from the crop areas; it consists of effective rainfall in the rainfed areas; and effective rainfall and irrigation CWU in the irrigated areas. The total crop ET is the sum of crop water requirements in different periods of crop growth. This analysis uses monthly climatic data to estimate crop water requirements in four different growth periods: Initial, development, middle and final stage (Amarasinghe et al. 2007b).

Step 7 estimates the physical water productivity (WP), which is the ratio of total production to total CWU.

Step 8 estimates the water demand for crop production. It assumes various scenarios of growth in the WP of rice cultivation, and estimates future water demand for the predicted crop demand.

Data

The time series (1961-2009) of calorie intakes for ARIMA modeling are taken from the food balance sheets of the FAOSTAT database (FAO 2013a). These include per capita calorie supply of cereals and rice, wheat, maize, pulses, vegetable oil, vegetables, fruits, starchy roots and sugar, and animal products. The food, feed and waste statistics are taken from the commodity balances of the FAOSTAT database (FAO 2013c). These include total food, feed, seed, waste and other uses of the above crops.

District is the basic unit for estimating crop CWU. Data on the total crop area and irrigated area of rice, wheat, maize, pulses, vegetable oil,

vegetables, fruits, starchy roots and sugarcane at the district level are taken from the Bangladesh Bureau of Statistics (BBS). Various publications by BBS provide the reference ET and rainfall data at district level.

Only the time series data from 1971 to 2012 for ARIMA modeling of the rice area, yield and production area were available at the national level from the Bangladesh Rice Knowledge Bank (BRKB) (BRRI 2013).

Food Demand

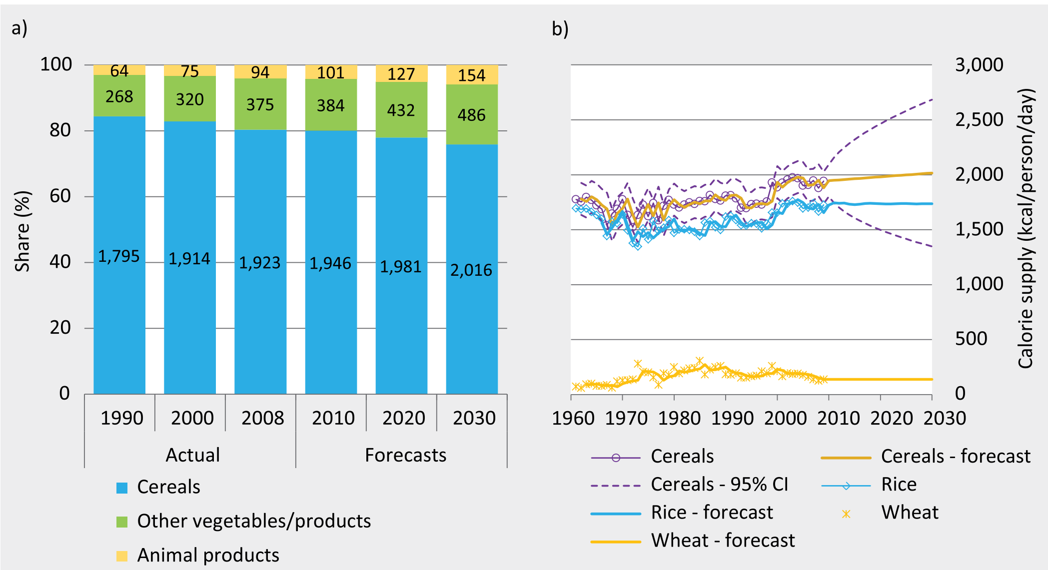
Composition of Calorie Supply

Food consumption in Bangladesh is slowly diversifying. Cereals still provide a major part of the calorie intake, but their share in calorie supply has decreased from 84% in 1990 to 80% by 2008 (Figure 2(a)). The contribution from other vegetables/products and animal products increased slightly to approximately 16% and 4%, respectively, of the total calorie supply in 2008.

The ARIMA[2] forecasts show that the share of calorie supply from cereals will reduce to about 76% of the total by 2030 (Figure 2(a)). However, the absolute supply will increase by 90 kcal/person/day - a 5% increase from the level in 2008. Consumption of rice and wheat increases by only 27 and 4 kcal/person/day, respectively (Figure 2(b)). Consumption of maize has increased rapidly in recent years; accordingly, maize will contribute the most to the total increase in cereal consumption - 62 kcals/person/day.

The share of calorie supply from cereals seems to be reaching a level of saturation. In fact, according to the food balance sheets of

FIGURE 2. (a) Composition of calorie supply (kcal/person/day), and (b) per capita calorie supply from cereals.



Sources: Per capita calorie supply up to 2008: FAO 2013c; forecasts are authors' estimates.

Note: CI – Confidence interval.

[2] The estimated parameters are available in Annex, Table A1.

FAO, Bangladesh has the world's highest per capita rice consumption and Asia's highest per capita cereal consumption (FAO 2013a). This is partly due to high levels of poverty; when income is low, people tend to consume more cereals to meet the daily calorie requirements; in Bangladesh, this happens to be rice, because it is the dominant crop. However, as far as rice consumption is concerned, there is no room for significant increases in average consumption even with income growth; in fact, it may even start decreasing as in countries with similar consumption and economic growth patterns in Asia (Amarasinghe et al. 2007a).

However, consumption of non-cereal food items is increasing with income (Figure 3). Feeding people with animal products, especially meat-based diets, requires much more water to provide the same calorie intake than from cereal products. This analysis shows that the consumption of animal products (milk, fish and meat) and non-cereal crops/products followed a similar trend: no significant increase in calorie intake before the 1990s, but increased 2.37% and 2.28%, respectively, annually, between 1990 and 2008.

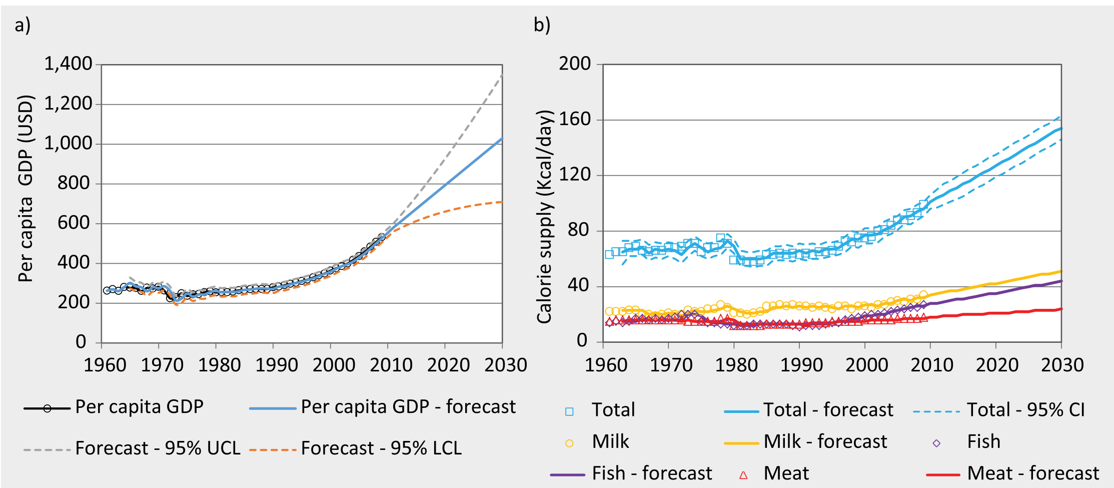
The ARIMA model forecasts per capita GDP to more than double by 2030 (Figure 3(a)); it will increase 3.1% (95% confidence interval 1.1% - 4.1%) annually between 2008 and 2030. The model forecasts calorie intake from animal products to increase 2.18% annually after 2008; it will reach 154 kcal/person/day by 2030, of which milk, fish and meat contribute to 74% (Figure 3(b)). The calorie supply from non-cereal crop products will also increase by 30% or 110 kcal/person/day by 2030, of which vegetables, vegetable oil, starchy roots and sugar make the largest contribution.

The projected total calorie supply for 2030 is 2,650 kcal/person/day. This level is adequate for achieving food security for all the people. The minimum recommended calorie intake for achieving food security in Bangladesh is 2,180 kcal/person/day (http://www.foodsecurityatlas.org/bgd/country). Those with a calorie intake less than 2,122 kcal/person/day are the absolute poor (BBS 2005). When average calorie supply reaches 2,700 kcal/person/day, food insecurity and poverty become insignificant even among the lowest income groups (Seckler et al. 1998).

Food Consumption

Table 2(b) provides food demand projections, which are the product of calorie supply and food to calorie conversion ratios. The food to calorie conversion ratios are the averages of the conversion ratios from 2006 to 2008.

FIGURE 3. Actual and forecasts of (a) per capita GDP of Bangladesh, and (b) per capita calorie supply from animal products.



Sources: Per capita GDP (in 2000 constant prices) up to 2009: World Bank 2013; per capita calorie supply up to 2008: FAO 2013c; and forecasts up to 2030 are authors' estimates.

Note: CI – Confidence interval; UCL – Upper confidence limit; LCL – Lower confidence limit.

In 2008, rice consumption was 172 kg/person/year[3]. The forecast shows only a negligible increase (2 kg/person/year) in rice consumption by 2030.

Consumption of wheat (the other major cereal), with only 16 kg/person/year, will also not change significantly by 2030. Other cereals, especially maize, show a significant increase from its low base: from about 8 kg/person/year in 2008 to 14 kg/person/year in 2030. Overall, cereal consumption is forecast to increase only by 8 kg/person/year between 2008 and 2030.

Of the other crop products, vegetables and starchy roots will have the highest increase in consumption: from 25 kg/person/year to 77 kg/year/person for vegetables, and from 35 kg/person/year to 56 kg/person/year for starchy roots between 2008 and 2030. Pulses, vegetable oils and sugar consumption will not increase much - only 1 kg/person/year by 2030.

Overall, calorie intake per person from animal products is forecast to increase by 64%, milk by 59%, fish by 69% and meat by 41% between 2008 and 2030. These have significant implications on feed demand, which until now mainly consisted of crop residues.

Total Food and Feed Demand

Total food demand is the product of per capita food demand and the population. The population of Bangladesh was 145 million in 2008; it will increase to 167 million by 2020 and 182 million by 2030 under the median population projection scenario. Accordingly, the total demand for rice for consumption in 2030 will be 31.7 MMt, which is a 24% increase from the 2008 level (Table 2(c)). The food demand for wheat will increase by 0.65 MMt from the 2008 consumption level. On the other hand, the food demand for coarse cereals, mainly maize, will increase 1.46 MMt (or by 124%) from the 2008 level.

Overall, the cereal demand for food is forecast to increase 8.84 MMt (or 31%) between 2008 and 2030. Of the other vegetable crops, the food demand for pulses will increase by 38%, vegetables by 286%, fruits by 26%, starchy roots by 103%, vegetable oils by 43% and sugar by 24% (Table 2(c)).

Feed demand is the product of calorie supply from animal products and the feed to calorie conversion ratios. Feed demand for rice and other coarse cereals, mainly maize, will increase by 104% by 2030. According to the analysis of pulses and oil cakes for feed, the feed demand for pulses will have a negligible increase from its low values now and the feed demand for oil cakes will increase by 104%. This analysis used the feed conversion ratios of 2008 for projecting future feed demand (Table 2(d)).

Total Crop Demand

Total crop demand is the product of food and feed demand, and the demand for other uses. Other uses mainly consist of seed, processing and waste. This paper uses the ratio of other uses to food and feed demand in 2008 to project the future crop demand (Table 2(c)).

The total demand for rice will increase by 5.4 MMt between 2008 and 2020, and another 3.3 MMt between 2020 and 2030. Demand for other cereals, mainly maize, will increase significantly by 1.1 MMt between 2008 and 2020, and a further 1.2 MMt by 2030.

In this study, the projection of total demand for rice is comparable with the estimate of the “Business as Usual” scenario (39-41 MMt) of Ganesh-Kumar et al. (2012). However, Ganesh-Kumar et al. (2012) projected a significantly higher increase in the per capita consumption of rice – about 188 kg/person/year by 2030; this is equivalent to an average increase of 8 kg/person/year per decade in the next two decades, whereas it has increased only about 3 kg/person/year in the last decade. The projections made by Ganesh-Kumar et al. (2012) for feed, seed, waste and other uses is about 5 MMt, which is similar to the level of 2008 and a highly unlikely scenario given the increasing consumption of animal products.

[3] This refers to the amount of food, in terms of quantity and it's derived products available for each individual in the total population (FAO 2013a), which is slightly different from the estimated per capita rice consumption from the Household Income and Expenditure Survey (HIES) (BBS 2010b). For example, rice consumption per person in 2005 from the FAO food balance sheets is 170 kg/year, while that estimated from HIES is 160 kg/year.

TABLE 2. Consumption of food, feed, crop and animal products, and demand projections for Bangladesh.

Factor	Year	Cereals (products)			Other crops (products)							Animal products			
		Rice	Wheat	Other cereals	Pulses	Vegetables	Fruits	Starchy roots	Vegetable oils	Oil crops	Sugar	Milk	Fish	Meat	Total
(a) Calorie intake (kcal/person/day)	2000	1,683	212	19	43	9	14	43	143	68	43	26	19	16	77
	2008	1,711	134	79	47	22	30	68	124	84	47	32	26	17	94
	2020	1,736	138	107	52	48	30	84	135	83	52	34	28	18	127
	2030	1,737	138	141	52	69	30	110	142	83	52	51	44	24	154
Food conversion ratio (grams/kcal)[1]	2008	0.28	0.32	0.28	0.29	3.07	2.17	1.4	0.11	0.29	0.29	1.59	1.55	0.63	-
(b) Food demand (kg/person/year)	2000	169	25	2	5	10	11	22	6	7	5	15	11	4	-
	2008	172	16	8	5	25	24	35	5	9	5	19	14	4	-
	2020	174	16	11	6	54	24	43	5	9	6	24	20	5	-
	2030	174	16	14	6	77	24	56	6	9	6	30	25	6	-
(c) Total food demand (MMt)	2000	21.9	3.2	0.3	0.6	1.3	1.5	2.9	0.8	2.9	0.9	1.9	1.4	0.4	-
	2008	25.0	2.3	1.2	0.7	3.7	3.5	5.0	0.7	3.0	1.3	2.7	2.1	0.6	-
	2020	29.2	2.7	1.8	0.9	9.0	4.0	7.2	0.9	3.5	1.5	4.1	3.3	0.8	-
	2030	31.7	2.9	2.6	1.0	14.1	4.3	10.2	1.0	4.0	1.6	5.4	4.5	1.0	-
Feed conversion ratio (grams/kcal)[2]	2008	0.31	-	0.13	-	-	-	-	0.10	-	-	0.09	-	-	-
(d) Total feed demand (MMt)	2000	0.5	-	0.0	-	-	-	-	0.1	-	-	0.4	-	-	-
	2008	1.5	-	0.7	-	-	-	-	0.4	-	-	0.5	-	-	-
	2020	2.4	-	1.0	-	-	-	-	0.7	-	-	0.7	-	-	-
	2030	3.1	-	1.3	-	-	-	-	1.0	-	-	0.9	-	-	-
Ratio of (seed + waste + other uses) (%)[3]	2008	8.6	10.3	12.6	3.6	8.7	10.3	23.1	-	-	-	7.6	0	-	-
(e) Total demand (MMt)	2000	18.1	2.8	0.1	0.6	1.1	1.5	1.8	0.9	2.9	0.9	2.1	1.4	0.4	-
	2008	30.0	2.5	2.1	0.8	4.0	3.8	6.2	1.1	3.0	1.3	3.4	2.1	0.6	-
	2020	35.4	3.0	3.2	1.0	9.8	4.4	8.8	0.9	3.5	1.5	5.2	3.3	0.8	-
	2030	38.7	3.2	4.4	1.0	15.1	4.7	12.2	1.0	4.0	1.6	6.9	4.5	1.0	-

Sources: Data for 2000 and 2008: FAO 2013a; Forecasts for 2020 and 2030 are authors' estimates.

Notes: [1] Food conversion ratio of 2008 shows the quantity of food required to provide one kilocalorie of nutritional intake; Conversion ratio of other cereals is that of maize.

[2] Feed conversion ratio of 2008 is used for projecting future feed demand; feed demand under vegetable oils is the demand for oil cakes, which is a by-product of vegetable oil production; only rice, maize and milk are the primary feed products.

[3] Ratio of (seed + waste + other uses)/(feed + food) are values in 2008; no waste was reported for oil crops, sugar, fish and milk.

Food Supply

Cropping Patterns

The preeminent position of rice in cropping patterns characterizes agriculture in Bangladesh (Figure 4). Rice occupies nearly 80% of the gross cropped area (GCA) and gross irrigated area (GIA), and accounted for 93% and 77% of the total increases in GCA and GIA, respectively, between 1990 and 2010. Therefore, this analysis only projects the supply of rice. Among the rice crops:

- *Aus* rice area decreased rapidly and is only 9% of the GCA now;
- *Aman* rice area accounts for the largest portion of GCA (40% in 2010); and
- *Boro* rice expanded rapidly, mainly at the expense of *Aus* rice.

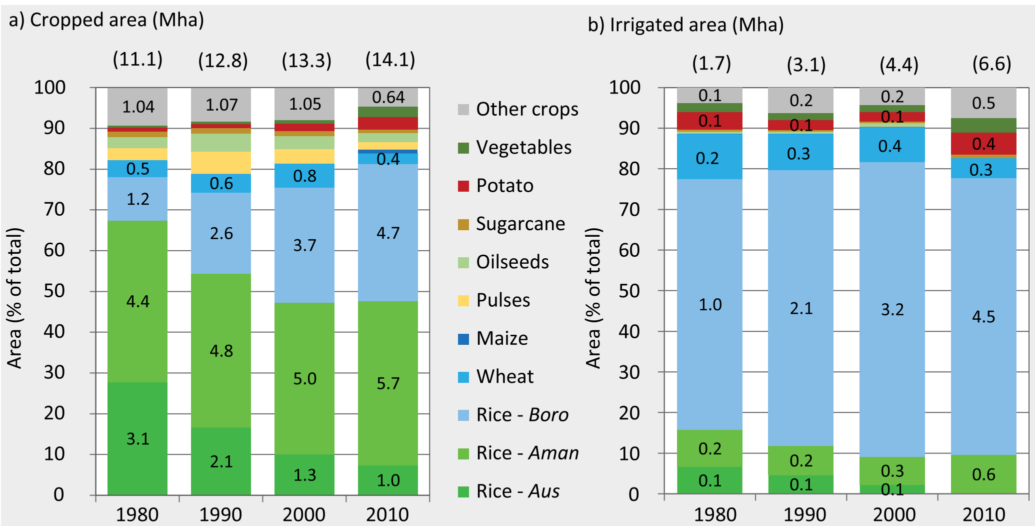
ARIMA models (Annex, Table A1) predict the following:

- A further decline in the *Aus* rice area (to 0.7 Mha by 2020 and 0.2 Mha by 2030).
- No significant changes in the *Aman* rice area. It is likely to stabilize between 5.7 to 6.1 Mha.
- A further increase in the *Boro* rice area (to 5.7 Mha by 2020 and another 1 Mha by 2030). The predicted increase in the *Boro* rice area will be significantly more than the decline in the *Aus* rice area (Figure 5(a)).

According to the ARIMA forecasts, the total rice area will increase to 12.5 Mha by 2030; an additional 1.1 Mha from the present level and the *Boro* rice area (6.7 Mha) will contribute to almost all of this expansion. However, this decline in *Aus* rice could be checked, especially in areas with *Rabi* crops such as wheat, maize, pulses and oil crops, by using short-duration rice varieties before the cultivation of *Aman* rice (Prof. Sattar Mandal, former Member of the Planning Commission, Government of Bangladesh, pers. comm. March, 2014).

Realistically, the increase in *Boro* rice will not be possible due to the increasing population, urbanization and land constraints. The Bangladesh Rice Research Institute (BRRI) projects that the total rice area will reduce to about 10.3 Mha by 2020 (BRRI 2013). The study carried out by the International Food Policy Research Institute (IFPRI) (Ganesh-Kumar et al. 2012) assumes that the *Boro*

FIGURE 4. Changes in (a) cropping, and (b) irrigation patterns in Bangladesh.



Sources: Bangladesh Bureau of Statistics.

Note: Cropping patterns indicate the three-year averages of 1979-1981, 1989-1991, 1999-2001 and 2009-2011. Values within parenthesis at the top of the bars are the gross cropped and irrigated area of Bangladesh. Values inside the bars are the absolute cropped area.

rice area can increase up to 6.5 Mha and the total rice area up to 12.6 Mha. While the extent of the projected expansion varies, all studies confirm that the main path to increasing rice production in the future is mainly through yield increases.

Rice Yield

Yield increases were a major contributor to production growth over the last few decades. Average rice yield increased 2.7% annually in the 1990s and 2.8% thereafter; over the same periods, rice production increased 2.9% and 3.6% respectively. Between 1970 and 2010, the increase in yield alone contributed to 77% of the production growth; and other contributions of 9% from an expansion in the area cultivated alone, and 14% from both yield and expansion in the cultivated area.

The following factors contributed to the increase in average rice yield:

- Changes from low-productive *Aus* rice to high-productive *Boro* rice; the latter produces 112% more yield (Figure 5(a)).
- Increase in rice yields in all the seasons (Figure 5(b)). Between 1990 and 2010, the yield of *Aus* rice increased 2.6% annually, while that of *Boro* and *Aman* rice increased 2.3% and 1.8%, respectively, annually. These trends are likely to continue with the increasing use of high-yielding rice varieties and better management of other inputs (Alauddin and Sharma 2013).

The ARIMA models (Annex, Table A1) predict:

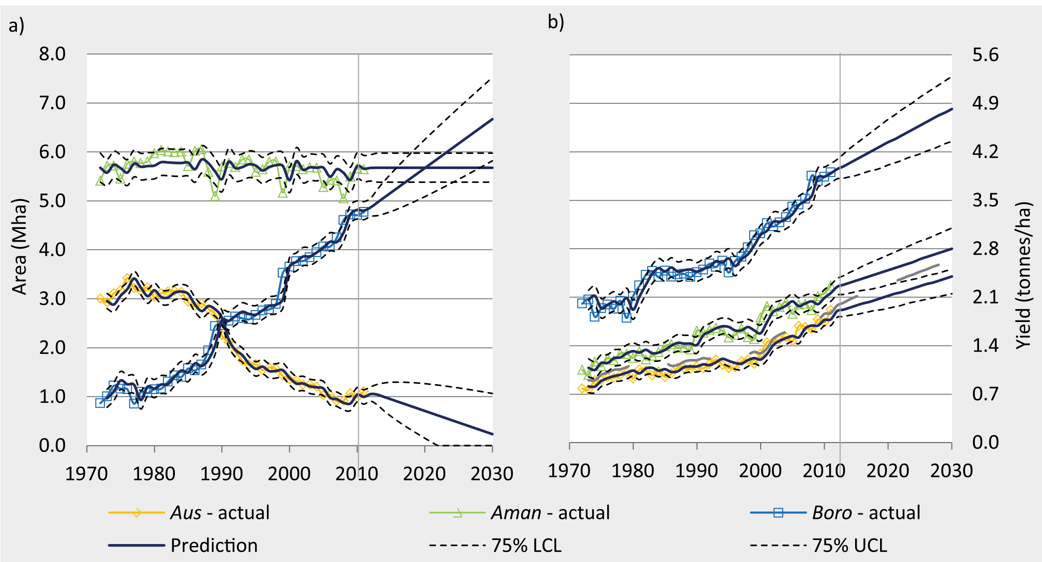
- Yield of *Aus* rice to increase 2.0% annually between 2010 and 2020; 1.2% annually in the 2020s; and to reach 2.4 t/ha by 2030.
- Yield of *Aman* rice to increase 1.8% and 1.1% annually in the next two decades, respectively, and to reach 2.8 t/ha by 2030; and
- Yield of *Boro* rice to increase 1.2% and 1.0% annually in the next two decades, respectively, and to reach 4.8 t/ha by 2030.

The projections of rice yield above assume that factors that contributed to growth in the past, such as advances in technology and high-yielding rice varieties, will continue to be developed and contribute to yield increases.

Rice Production

Bangladesh is self-sufficient in rice now (Figure 6). Rice production was 5% less than the demand

FIGURE 5. (a) Area, and (b) yield of rice in the *Aus*, *Aman* and *Boro* seasons.



Sources: 1972-2011: Bangladesh Rice Knowledge Bank (http://www.knowledgebank-brri.org/); 2011-2030: authors' estimates.

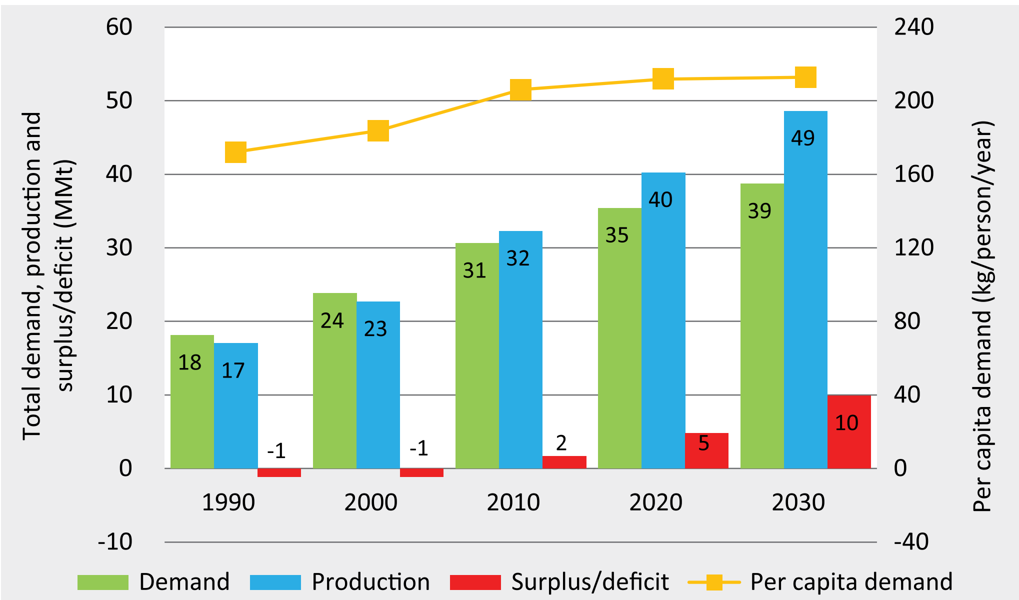
Notes: UCL - Upper confidence limit; LCL – Lower confidence limit.

in 2000, but there was a surplus of 5% in 2010. With the projected increases in area and yield, Bangladesh can even have substantial production surpluses - 14% of the demand in 2020, and 26% of the demand in 2030. This is quite a positive outlook, given that there are arguments for revisiting self-sufficiency than the policy of self-reliance for food (Deb et al. 2009). The self-reliance policy, introduced in the early 1990s, permitted imports when the world market prices were cheaper than the cost of growing locally.

However, a contentious point in the above projection is the area expansion, mainly that of *Boro* rice. With increasing pressure on land due to urbanization and development, it is not clear whether such a horizontal expansion of area is possible. However, with the forecasts of yield growth, self-sufficiency of rice is possible even without this area expansion. Even under the pessimistic scenarios of lower growth in yield, i.e., say along the 75% LCL (Figure 5(b)), the total rice production of 39 Mt would be more than sufficient to meet the total demand by 2030.

Boro rice is irrigation intensive. Therefore, it is appropriate that Bangladesh restricts the *Boro* rice area only to achieve self-sufficiency. This saves both land and irrigation for increasing the production of other crops. These resources can be used to increase the production of vegetables, roots and tubers, which will have substantial increases in demand, and are important for nutritional security and dietary diversification.

FIGURE 6. Rice demand, production and production surpluses/deficits.



Water Demand

Consumptive Water Use

This analysis assesses future agricultural water demand under two scenarios of increases in WP: (i) area expansion and surplus rice production; and (ii) self-sufficiency in rice production, improving water productivity with no area expansion. All scenarios assumed average rainfall conditions. Monthly average rainfall in 1999-2001 closely followed the long-term monthly averages

between 1969 and 2004 (Figure 7). Therefore, the analysis selected the period 1999-2001 to estimate the base-year WP.

Table 3 provides the components of total CWU in 1999-2001, which include rainfall CWU in rainfed areas, and the rainfall and irrigation CWUs in irrigated areas. Some salient features are given below:

- Rice production accounted for 93% of the total CWU and 90% of the total irrigation CWU.
- *Boro* rice accounted for almost all the irrigation CWU of rice. *Aus* and *Aman* rice have some irrigated area. However, climatic data show that these seasons require hardly any irrigation (no irrigation CWU for *Aman* rice, and only 13 mm for *Aus* rice). Here, farmers try to manage unreliable rainfall with supplementary irrigation, for which water availability during these periods is not a major issue.
- CWU of *Boro* (598 mm) is 31% and 10% more than the CWU of *Aus* and *Aman* rice. Effective rainfall contributes to only 38% (=230/598) of the total CWU of *Boro* rice. The balance is from irrigation.
- *Boro* rice has the highest physical WP (0.56 kg/m^3), which is 52% and 84% more than *Aman* and *Aus* rice, respectively. The differences in WP are relatively lower than that of yield, because the additional water consumption in *Boro* rice is more than the increase in yield. The study by Alauddin and Sharma (2013) showed that a large potential still exists for improving rice water productivity in several districts of Bangladesh.
- There is a trade-off of abandoning the production of *Aus* rice in favor of *Boro* rice, which is the current trend now. This increases production, but requires substantially more irrigation.
- Increasing the *Boro* rice area is essential for rice self-sufficiency. However, the challenge is to find the area to increase the *Boro* rice extent. Thus, first, the emphasis should be on increasing yield in all rice-growing areas. Second, shifting rice production from the *Aus* to the *Boro* season.

FIGURE 7. Average monthly rainfall and ET, and P75 rainfall.

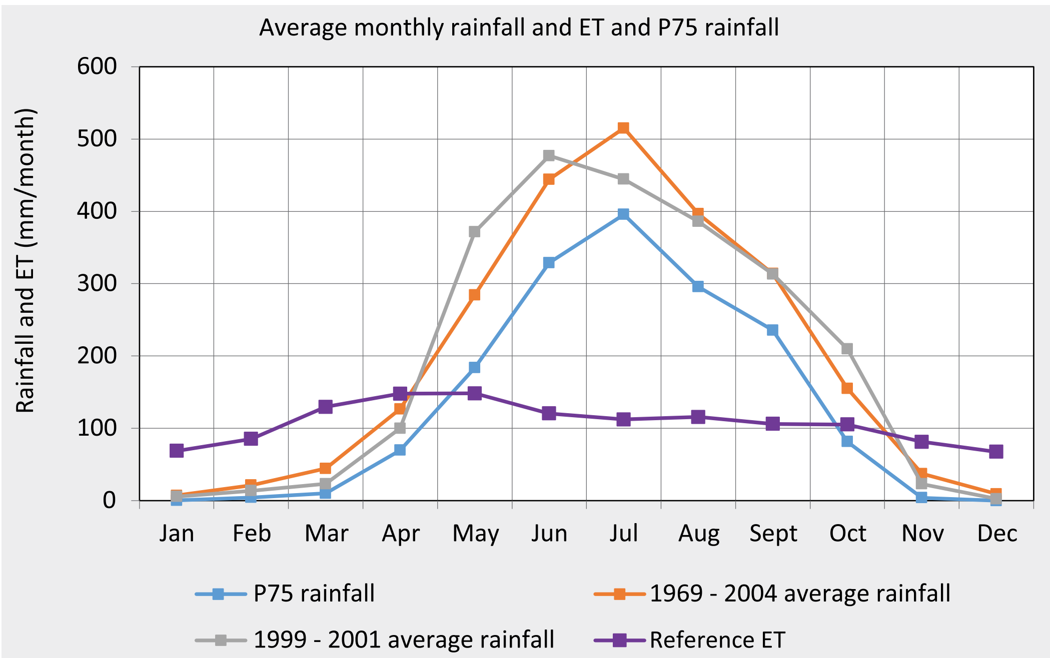


TABLE 3. Crop production, water use and productivity of major crops in Bangladesh (1999-2001).

Factor	Unit	Crops													
		Aus rice	*Aman* rice	*Boro* rice	Total rice	Wheat	Maize	Other cereals[1]	Pulses	Oil seeds[2]	Sugar-cane	Pota-toes	Vegeta-bles	Other crops[3]	Total
Rainfed area	Mha	1.24	4.65	0.52	6.41	0.40	6.00	0.13	0.47	0.39	0.15	0.14	0.05	0.72	8.87
Irrigated area	Mha	0.10	0.31	3.22	3.63	0.38	0.005	0.004	0.004	0.03	0.02	0.10	0.07	0.19	4.43
Crop growth period	Days	120	150	150	-	120	150	120	90	100	330	120	120	-	-
Starting date[4]	Day	Apr	Jul	Dec	-	Oct	Apr	Apr	Aug	Jun	Dec	Sep	Jun	-	-
			01	01	15	01	01	01	21	21	01	15	15		
Rainfall CWU in rainfed areas	Bm^3	5.6	25.2	1.3	32.2	0.3	0.0	0.2	0.5	0.4	1.5	0.6	0.1	2.1	37.8
Rainfall CWU in irrigated areas	Bm^3	0.5	1.7	7.4	9.6	0.2	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.4	10.7
Irrigation CWU in irrigated areas	Bm^3	0.0	0.0	11.8	11.8	0.9	0.0	0.0	0.0	0.1	0.0	0.1	0.1	0.2	13.2
Total CWU in all areas	Bm^3	6.1	26.9	20.5	53.6	1.3	0.0	0.2	0.5	0.5	1.7	0.8	0.4	2.7	61.7
Total CWU in rainfed areas	mm	456	542	247	499	66	143	119	108	105	1,003	383	290	-	-
Total CWU in irrigated areas	mm	485	555	598	591	274	373	370	302	242	1,209	207	346	-	-
Irrigation CWU in irrigated area	mm	13	0	230	265	53	98	105	64	69	1,010	153	213	-	-
Total production	MMt	1.9	9.9	11.5	23.3	1.7	0.0	0.1	0.4	0.4	6.7	3.1	0.8	-	-
Total yield	t/ha	1.4	2.0	3.1	2.3	2.2	2.5	0.9	0.8	0.9	39.9	12.4	6.4	-	-
Water productivity	(kg/m^3)	0.30	0.37	0.56	0.44	1.29	1.00	0.71	0.71	0.79	3.88	3.98	1.96	-	-
Water productivity[5]	(USD/m^3)	0.06	0.07	0.10	0.08	0.20	0.16	0.11	0.28	0.29	0.07	0.42	0.27	-	-

Sources: Crop area, production and growth patterns are from the Bangladesh Bureau of Statistics (BBS 2010a). Producer prices are from FAO 2013c. Total and irrigation CWU, and water productivity are authors' estimates.

Notes: [1] Pulses mainly have two seasons: *Kharif* season (90-day crop) starts in August, and *Rabi* season (130-day crop) starts in November.

[2] Oilseeds mainly have three seasons: *Kharif* season (100-day crop) starts in June, *Rabi* season (90-day crop) starts in December, and the summer season (90-day crop) starts in February.

[3] Other crops include non-food crops, fodder, etc. CWU here is based on the CWU of vegetables.

[4] This starting date is used for estimation of CWU.

[5] Prices are the average producer prices in 1999-2001.

Water Productivity

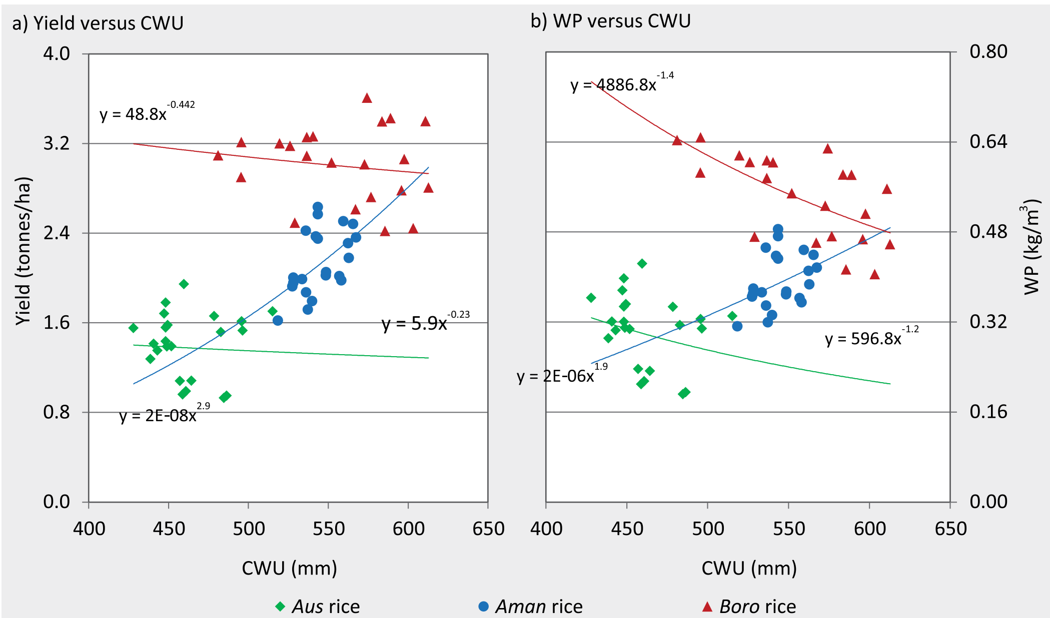
Improving WP would not necessarily increase production (Amarasinghe and Smakhtin 2014). This is especially true if both yield and CWU are high, and a marginal increase in yield with respect to CWU, or marginal WP, is low or negative. However, Bangladesh has the potential to improve both WP and production. Figure 8 shows the variation of WP and yield with total CWU of *Aus*, *Aman* and *Boro* rice across 23 districts in Bangladesh. Figure 8(a) shows that the districts with higher CWU have higher yields in *Aman* rice, but tend to have lower yields in Boro rice. Figure 8(b) shows that WP increases with CWU in Aman rice, but decreases significantly in *Boro* rice. Thus, there are two possible ways of increasing both water productivity and rice production.

1. Increase WP in *Boro* rice. Abandoning rainfed *Aus* rice for irrigated *Boro* rice provides a higher yield and production. Many districts with *Boro* rice have substantially high irrigation CWU (550-600 mm range (Figure 8)), but substantially lower yield than the average *Boro* rice yield of 3.1 t/ha. These districts can reduce irrigation. For example, a 50-mm reduction in irrigation CWU in *Boro* rice can reduce 10-20% of total irrigation CWU, while still maintaining a similar yield. This increases both production and WP.

2. Increase WP in *Aman* rice. Given the large area under Aman rice, a slight increase in yield would reduce the requirement for the area under irrigated *Boro* rice. For example, changing cropping patterns from 1 Mha of *Aus* rice to *Boro* rice (which is the current trend) increases production by 1.7 Mt, but it requires 2.3 Bm^3 of irrigation CWU. However, by providing 25 mm of supplemental irrigation in 2 Mha of *Aman* rice would require only 0.5 Bm^3 of irrigation CWU, but could increase production anywhere between 1 to 1.5 Mt. A slight increase in CWU can increase yield and WP of *Aman* rice. So, a proper combination of cropping patterns in *Aus* and *Aman* rice, with a small amount of supplemental irrigation in the *Aman* season, can increase both WP and production. In fact, for long-term sustainable water use, it may be a good idea to improve the productivity of *Aman* rice, especially in the districts where there is a large potential.

This potential of improving WP can be used for developing various scenarios of future water demand.

FIGURE 8. Variation of (a) yield, and (b) WP with total CWU across 23 districts in Bangladesh.



CWU Demand of Rice Production

The irrigation CWU of rice production, which was 11.8 Bm^3 in 2000 (Table 3), has increased by 40% to 16.5 Bm^3 in 2010 (Table 4); the latter is estimated using the irrigation CWU per hectare of 265 mm in 2000 (Table 3). This analysis estimates irrigation CWU demand to 2020 and 2030 under two different scenarios:

Scenario 1: Area expansion and surplus rice production: This scenario assumes that the area and yield of rice will increase as projected in the section, *Methodology and Data*. This means that the irrigated area will increase only in *Boro* rice: from 4.5 Mha in 2010 to 5.7 Mha in 2020 and 6.7 Mha in 2030. The irrigation CWU demand for rice will be 20.9 Bm^3 and 24.5 Bm^3 in 2020 and 2030, which are 27% and 48% increases from the 2010 level, respectively.

Under the projected area and yield growth in all three seasons, this scenario will have a large rice surplus. However, rice has the lowest economic water productivity (Table 3, last row); groundwater for irrigation in the *Boro* season is getting scarce (Zahid and Ahmed 2006; Ali et al. 2012). Therefore, instead of producing large surpluses of rice, a better option would be to use that irrigation water for the production of high-value crops.

Therefore, the second scenario considers that the yield will increase at the same rate as in scenario 1. However, the rice area, especially in the *Boro* season, will expand only to meet the self-sufficiency of rice.

Scenario 2: Self-sufficiency in rice production, improving water productivity with no area expansion: According to this scenario, rice production will have to be 37.2 MMt by 2020 and 40.3 MMt by 2030, respectively; these estimates are 5% more than the projected consumption demand; and the additional 5% replenishes stocks. The assumption of self-sufficiency requires 3 MMt less production than in the "Business as Usual" scenario. This scenario analyzes irrigation CWU under different WP growth scenarios of 0%, 5% and 10%. These are potentially feasible, since increases in WP are possible in both *Boro* and *Aman* rice. If the saving in production that is

TABLE 4. Irrigation CWU demand under different scenarios of WP growth.

Time	Season	Area (Mha)		CWU (Bm^3)		Total production	Water productivity	Savings of irrigation CWU (Bm^3) by only meeting the rice demand[1]		
		Total	Irrigated	Total	Irrigation	(MMt)	(Kg/m^3)	WP growth scenarios[2] 0%	5%	10%
2010	*Aus*	1.1	0.0	4.8	0.0	1.9	0.40	-	-	-
	Aman	5.6	0.6	30.7	0.0	12.5	0.41	-	-	-
	Boro	4.7	4.5	27.5	16.5	18.3	0.67	-	-	-
	Total	11.4	5.1	63.0	16.5	32.8	0.52	-	-	-
2020	*Aus*	0.7	0.0	3.2	0.0	1.5	0.47	-	-	-
	Aman	5.7	0.0	30.8	0.0	14.1	0.46	-	-	-
	Boro	5.7	5.7	33.9	20.9	24.6	0.73	2.60	2.74	2.89
	Total	12.1	5.7	67.9	20.9	40.2	0.59	-	-	-
2030	*Aus*	0.2	0.0	1.1	0.0	0.6	0.53	-	-	-
	Aman	5.7	0.0	30.8	0.0	15.9	0.52	-	-	-
	Boro	6.7	6.7	39.9	24.5	32.1	0.81	6.08	6.40	6.76
	Total	12.6	6.7	71.7	24.5	48.6	0.68	-	-	-

Sources: The area and total production data for 2010 are from the Bangladesh Bureau of Statistics; Water productivity and CWU for 2010, and projections for 2020 and 2030 are authors' estimates.

Notes: [1] Rice demand in 2010, 2020 and 2030 are 30.2 MMt, 37.2 MMt and 40.3 MMt, respectively.

[2] WP growth scenarios are only assumed for *Boro* rice.

made from self-sufficiency is from *Boro* rice then the following will be true:

- Even with no growth in WP, irrigation CWU demand will decrease by 2.6 Bm^3 and 6.1 Bm^3 by 2020 and 2030, respectively, from the estimates in scenario 1, due to lower production requirement;
- With 5% growth in WP, irrigation CWU demand will decrease by 2.7 Bm^3 and 6.4 Bm^3 by 2020 and 2030, respectively; and
- With 10% growth in WP, irrigation CWU demand will decrease by 2.9 Bm^3 and 6.8 Bm^3, respectively.

Importantly, the reduced irrigation CWU of rice in scenario 2 can meet most of the irrigation demand of other crops. The other three major irrigated crops are wheat, vegetables and potatoes: (a) the additional demand for these crops would be 0.7 MMt, 11.1 MMt and 4.0 MMt, respectively (Table 2); (b) the water productivity of these crops is 1.29 kg/m^3, 1.96 kg/m^3 and 3.98 kg/m^2, respectively (Table 3); and (c) the additional CWU demand (crop demand/water productivity) of these crops is 0.5 Bm^3, 1.5 Bm^3 and 5.7 Bm^3, respectively. Since irrigation contributes to 19%, 74% and 62% of the total CWU, the total additional irrigation CWU of these three crops is 4.9 Bm^3, which is less than the reduction in CWU of rice in scenario 2. Indeed, demand management taking into consideration food demand and production can substantially reduce the irrigation demand. However, there are still water supply constraints that need to be addressed.

Groundwater is the source for more than 75% of the irrigated area (BBS 2011). Thus, groundwater would have contributed to about 13 Bm^3 of irrigation CWU in 2010. A large part of this CWU is from natural recharge, and the balance is from return flows of surface water irrigation. If the current share of groundwater irrigation was to continue, this would require at least 14-16 Bm^3 by 2020 and 14-19 Bm^3 by 2030. Besides this, domestic and industrial water demand will also increase. Therefore, a pertinent question is whether there are adequate renewable groundwater resources to meet the increasing demand.

Given the falling groundwater tables and water quality issues in Bangladesh, it will be extremely difficult to exploit groundwater resources sustainably under scenario 1. Without an increase in WP, it will be difficult to meet even the reduced demand under scenario 2. Alauddin and Sharma (2013) also raised similar concerns about the unsustainable use of groundwater for increasing *Boro* rice production without sufficiently improving water productivity. These are mainly the districts with very high irrigation CWU at the moment. Karimov et al. (2014) showed that, in these districts, a carefully planned deficit irrigation regime can increase the transpiration and hence crop yield, under full irrigation using groundwater.

Comparison of irrigation CWU and usable groundwater recharge (Annex, Table A2) show that a few districts have already passed the sustainable thresholds of groundwater use. These districts include Khulna in the Khulna region, and Bogra and Pabna in the Rajshahi region, where irrigation CWU exceeds the usable groundwater recharge. In a few other districts, such as Barisal, Chittagong, Kishoreganj, Kushtia and Rajshahi, groundwater withdrawals for irrigation may exceed the usable recharge.

Of course, demand management is necessary, but is not sufficient to reduce the stress on groundwater resources. Groundwater not only provides irrigation, it also meets domestic, industrial and environmental water needs. It is imperative to increase groundwater recharge artificially or develop surface water resources. Can the country retain a small portion of flows during the monsoon season to increase recharge and augment river flows? The monsoon flows account for nearly 80% of the total surface runoff of 1,100 Bm^3; retaining a small portion of this as recharge would not have a huge effect on the environment; rather, it could increase environmental flows in the dry season, mitigate flood damages and increase overall social benefits. Further research needs to be conducted to identify to what extent this is possible and how such a program should be implemented.

Conclusions

To achieve food security and irrigation water management in Bangladesh, there is no crop more important than rice. This analysis forecasts a slowly changing rice consumption pattern. The change in the demand for rice for consumption (the main component) will be negligible, but the demand for rice for feeding animals will double. However, that increase will also remain a negligible quantity. Overall, the demand for rice, which includes food, feed, seed, waste and other uses, closely follows population growth and will increase 29% by 2030.

Given the present trends of area and yield, the analysis forecasts significant production surpluses by 2030 under the "Business as Usual" scenario. Production will exceed the requirement for self-sufficiency by 25%. Importantly, *Boro* rice will provide 88% of the additional demand.

However, substantial increases in the *Boro* rice area will have an effect on irrigation and the environment. If the present patterns of increase in the rice area and irrigation were to continue, the demand for irrigation CWU will increase by 48% by 2030. Of this, the groundwater CWU demand for irrigation alone will be about 19 Bm^3, which is at least 75% of the total irrigation CWU. Meeting this requirement without using groundwater unsustainably will be a major challenge in some areas.

However, if self-sufficiency becomes the main target, Bangladesh does not require such an increase in irrigation. Such a scenario with WP improvements can reduce irrigation demand substantially. This is because it requires a smaller *Boro* rice area and hence lower irrigation. In fact, with WP increases, it can save as much as 6 Bm^3 of groundwater irrigation CWU, which is more than sufficient to meet the additional irrigation CWU demand of all the other crops.

Irrigation CWU demand can also be reduced by improving water productivity, which is possible in both *Aman* and *Boro* rice. A small amount of supplemental irrigation can increase marginal water productivity of *Aman* rice; it increases yield, water productivity and production.

There is also some potential for reducing irrigation CWU in *Boro* rice in many districts without reducing the yield. This can be achieved through a carefully planned deficit irrigation supply to increase transpiration, which saves irrigation, and increases water productivity and production.

Given the large area under rice production, *Aman* rice has the biggest potential for increasing water productivity and production. This, in turn, requires lower production of *Boro* rice. Reduced production of *Boro* rice will lead to a decrease in irrigation and irrigation CWU.

A reduction in the *Boro* rice area and irrigation can increase the production of other crops. This irrigation can be used to meet the increasing demand for other major irrigated crops such as vegetables, roots and tubers. This analysis projects a 280% increase in vegetable demand and a 87% increase in roots and tubers.

It is clear that Bangladesh may require substantially more irrigation to meet future needs under the "Business as Usual" scenario. Proper planning of cropping patterns is necessary for reducing irrigation demand. Based on this analysis, it is recommended that agricultural and irrigation planning consider the following:

1. Increasing water productivity and production of *Aman* rice by providing a small amount of supplemental irrigation wherever necessary; in order to achieve this, target the districts with high CWU but lower rice yields. This reduces the requirement for increases in *Boro* rice and substantial groundwater irrigation.
2. Increasing the *Boro* rice area to the extent of maintaining self-sufficiency. Also, with carefully planned deficit irrigation practices, reduce irrigation in districts with high CWU and low yield. This reduces the irrigation requirement for rice in the *Boro* season. Such a reduction is difficult to realize at present, because *Boro* rice has high yield and is

remunerative. However, this situation can change with the increasing demand for high-value crops.

3. Diversifying cropping patterns in the *Boro* season to increase the production of vegetables and roots. The demand for these crops is increasing and they have substantially higher economic water productivity.

Finally, although this paper has not studied the situation of groundwater in detail, it is clear that availability of this resource will be a critical factor in irrigation and rice production. It is imperative that the country explores the potential of using a part of its vast surface water resources to put in underground aquifers. Much of that recharge will be available in the non-monsoon season, when water requirements for irrigation in the *Boro* season are the highest.

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Annex. ARIMA Model Estimation of Food Demand and Supply.

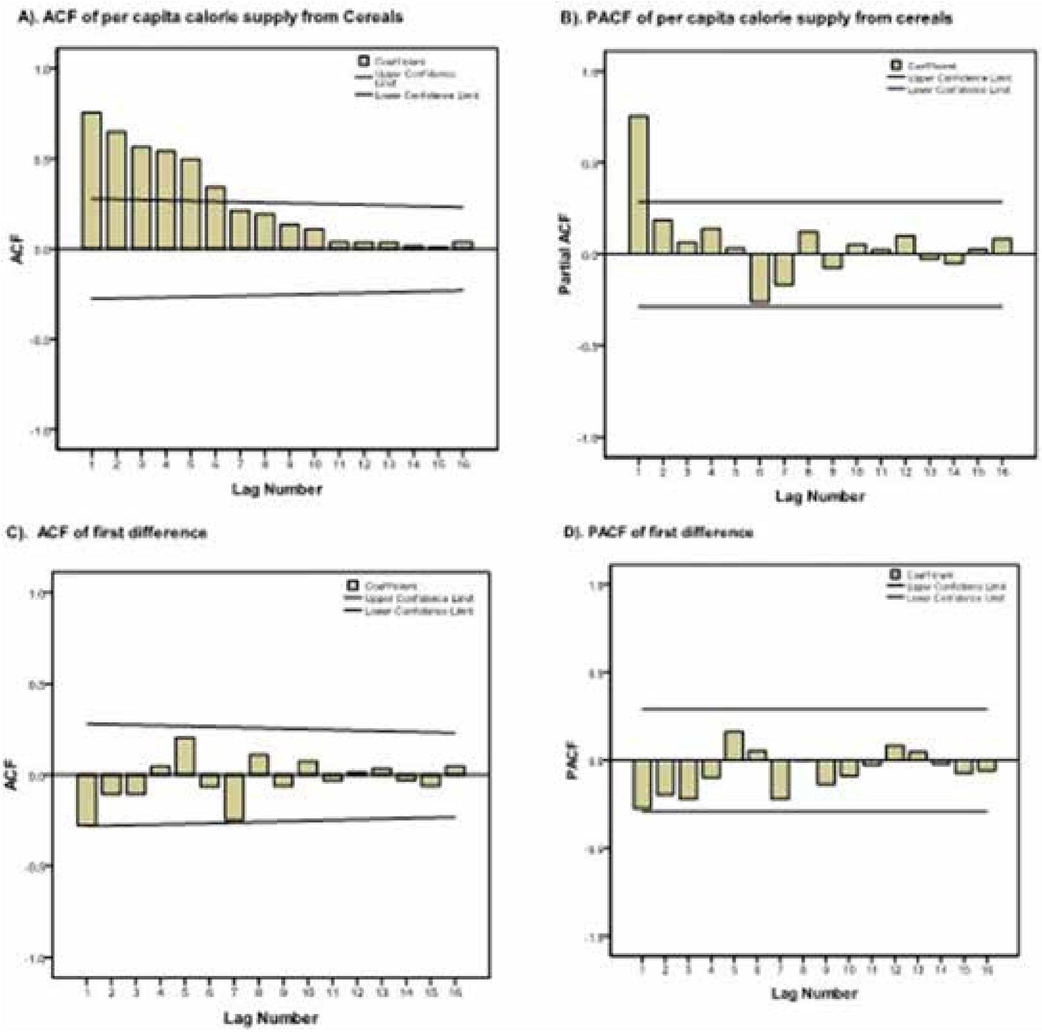
The description below shows the process of Autoregressive integrated moving average (ARIMA) estimation for per capita cereal consumption. Similar processes are applied for all other variables. The SPSS 17 Forecasting module is used for identifying the most parsimonious ARIMA model.

An ARIMA analysis uses stationary time series, i.e., those series without trends. A non-stationary time series would generally have non-zero autocorrelations (ACF) up to several lags. Number of non-zero partial autocorrelation functions (PACF) indicate the order of differencing required to make a series stationary. The per capita cereal consumption series is non-stationary (Figure A1(a)), but the first difference series is stationary (Figure A1(b)).

The next step in the analysis is to identify the moving average (MA) and autoregressive (AR) terms in the model. ACF and PACF of a stationary series determine the order of AR or MA or both. Exponentially decaying ACFs indicate an AR process, and non-zero PACFs indicate the order of the AR process. Exponentially decaying PACFs indicate an MA process, and non-zero ACFs show the order of the MA process. Exponentially decaying ACFs and PACFs indicate a mixed AR and MA process.

Exponentially decaying PACFs of the first-differenced per capita calorie supply (Figure A1(c)) indicates a MA process, and a single non-zero ACF coefficient shows that the process is

FIGURE A1. (a) ACF, and (b) PACF of per capita calorie supply from cereals; and (c) ACF, and (d) PACF of first difference.



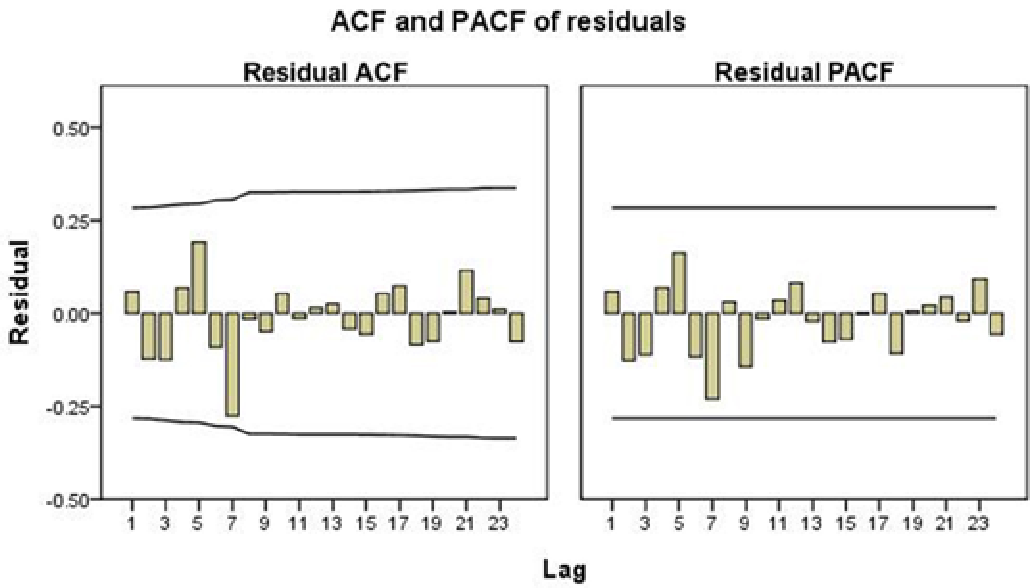
Sources: Authors' estimates.

in the order of 1. This shows that de-trended per capita calorie supply of cereals is a MA process in the order of 1, i.e., ARIMA (0,1,1).

The next step in the ARIMA model building is parameter estimation. This generally requires either least-squares or non-linear parameter estimation methods. The final step in the estimation process is diagnostic checking, i.e., to test whether the estimated model fits data adequately. This is indicated by statistically non-significant ACF and PACF coefficients of the residuals. Figure A2 shows that ACF and PACF of residuals of the ARIMA (0,1,1) model of per capita calorie supply of cereals is not significantly different from zero. The estimated coefficients of the ARIMA model are given in Table A1.

The ACF and PACF plots are general guidelines for determining the type and order of the ARIMA model. Sometimes, patterns of ACF and PACF plots and residual plots are not conclusive, and there can be more than one model explaining the series. The most parsimonious model is selected using the Normalized Bayesian Information Criterion (NBIC), which is Ln(MSE) + k Ln(n)/n, where MSE is mean squared error, k is number of parameters estimated and n is the number of observations.

FIGURE A2. ACF and PACF of residuals.



Sources: Authors' estimates.

TABLE A1. Estimated parameters of ARIMA models for food demand and supply.

Item	ARIMA model[a] (p,d,q)	Autoregressive parameters AR1	Moving average parameters MA1	MA2	Per capita GDP	R^2
GDP/person	Browns[b]	-	0.49 (0.06)***		-	0.98
Cereals – Total	(0,1,1)	-	0.44 (0.13)***	-	-	0.62
- Rice	(0,1,1)	-	0.38 (0.13)***	-	-	0.54
- Wheat	(0,0,2)	-	-0.55 (0.13)***	-0.42 (0.14)***	-	0.41
Animal products – Total	(1,0,0)	0.77 (0.09)***	-	-	0.12 (0.03)***	0.93
- Milk	(1,0,0)	0.71 (0.11)***	-	-	0.04 (0.01)***	0.82
- Fish		0.89 (0.06)***			0.04 (0.01)***	0.93
- Meat	(1,0,0)	0.79 (0.09)***	-	-	0.01 (0.005)**	0.73
Other crops						
- Pulses	(0,1,1)	-	0.42 (0.15)***	-	-	0.43
- Vegetable oils	(0,1,1)		0.43 (0.14)***			0.79
- Vegetables	(0,1,0)	-	-	-	-	0.97
- Sugar	(0,1,0)					0.78
- Roots	(0,1,0)	-	-	-	-	0.79
Rice area						
- Aus	(0,1,2)	-	-0.033 (0.161)	-0.294 (0.162)**		0.98
- Aman	(0,1,1)	-	-0.454 (0.161)***	-		0.18
- Boro	(0,1,0)	-	-	-		0.98
Rice yield						
- Aus	(1,0,0)	0.377 (0.16)**	-	-		0.94
- Aman	(1,0,0)	-	0.458 (0.153)	-		0.91
- Boro	-	-	0.241 (0.160)	-		0.96

Sources: Authors' estimates.

Notes: [a] The NBIC is used for selecting the final model.

[b] Per capita GDP is modeled using Brown's linear trend exponential smoothing model, which is similar to ARIMA (0,2,2).

*** and ** indicate significance at 0.005 and 0.05 level, respectively.

TABLE A2. Irrigated area, CWU and groundwater resources of districts.

Region	District	Cropped area	Irrigated area	Usable groundwater recharge[a]	Total CWU usable	Irrigation CWU Total	Irrigation CWU Percentage of groundwater recharge
		(1,000 ha)	(1,000 ha)	(Mm^3)	(Mm^3)	(Mm^3)	(%)
Bangladesh		13,870	6,741	68,982	67,101	17,322	25
Barisal		830	184	821	3,768	389	47
Chittagong		2,463	1,002	12,739	10,789	2,413	19
Dhaka		3,516	1,901	27,280	16,496	4,719	17
Khulna		1,577	977	5,674	8,148	2,529	45
Rajshahi		4,714	2,517	15,325	23,611	7,007	46
Sylhet		771	160	7,144	4,288	265	4
Barisal	Barisal	530	157	821	2,273	382	47
	Patuakhali	300	27	0	1,495	6	-
Chittagong	Bandarban	24	11	0	89	24	-
	Chittagong	450	158	1,017	2,621	436	43
	Comilla	55	20	9,421	254	44	0
	Khagrachhari	517	110	0	1,964	181	-
	Noakhali	43	10	2,301	212	24	1
	Rangamati	596	320	0	1,903	841	-
Dhaka	Dhaka	622	344	5,552	3,038	924	17
	Faridpur	465	244	4,680	1,605	575	12
	Jamalpur	584	325	4,382	2,925	899	21
	Kishoreganj	615	261	1,553	3,258	636	41
	Mymensingh	375	199	7,167	1,968	497	7
	Tangail	854	527	3,946	3,702	1,188	30
Khulna	Jessore	484	184	3,282	2,430	502	15
	Khulna	435	408	1,161	2,573	1,323	114
	Kushtia	657	385	1,231	3,145	704	57
Rajshahi	Bogra	988	528	1,542	5,886	1,642	106
	Dinajpur	520	284	3,128	2,507	662	21
	Pabna	1,150	746	1,694	4,574	2,103	124
	Rajshahi	1,200	629	4,340	6,432	1,749	40
	Rangpur	855	330	4,620	4,212	851	18
Sylhet	Sylhet	771	160	7,144	4,288	265	4

Sources: Cropped and irrigated areas are from BBS 2011; Usable groundwater recharge was compiled from BMDA 2004; Total and irrigation CWU are authors' estimates.

Notes: [a] The total usable groundwater recharge estimate of 69 Bm^3 in BMDA (2004), however, is substantially higher than the groundwater resources estimate of FAO's AQUASTAT database (FAO 2013d). Although details of the estimation of usable groundwater recharge are not available, it may include the recharge from irrigation withdrawals, which includes the deep percolation requirement for paddy. The latter was not factored into the estimate of irrigation CWU.

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