Climate sensitivity of wheat yield in Bangladesh: Implications for Sustainable Development Goals 2 (SDG2) and 6 (SDG6)

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Abstract

Significant manifestations of adverse effects of climate change exist for crop agriculture throughout the developing word including Bangladesh. Despite wheat being the second most important staple crop, any rigorous analysis of its sensitivity to climate change remains a neglected area. This paper fills this gap by investigating wheat yield sensitivity to climate change over time and across climatic zones using 45-year panel data; and exploring policy implications for achieving SDG2 (food security) and SDG6 (sustainable water management) through expanded wheat cultivation.

Average seasonal temperature and number of seasonal dry days trended upwards while rainfall (planting, flowering, harvesting) and bright sunshine trended downwards. Rise in average temperature, number of dry days, and relative humidity had adverse effects on wheat yield. Planting and flowering stage rainfall and sunnier weather conditions improved yield. Significant variations across regions and a positive time trend were evident implying technological progress. Strengthening institutional support systems, market accessibility, and science-driven climate change adaptation including generation and wider dissemination of drought tolerant wheat varieties, and enhancing farmers' capacity to switch from rice to wheat constitute key areas of policy intervention. This will help ensure food security alongside sustainable water management.

Keywords: Climate change, Wheat, Panel data, Food security; Sustainable water management Bangladesh

JEL classification: C33; O13; Q54

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1. Introduction

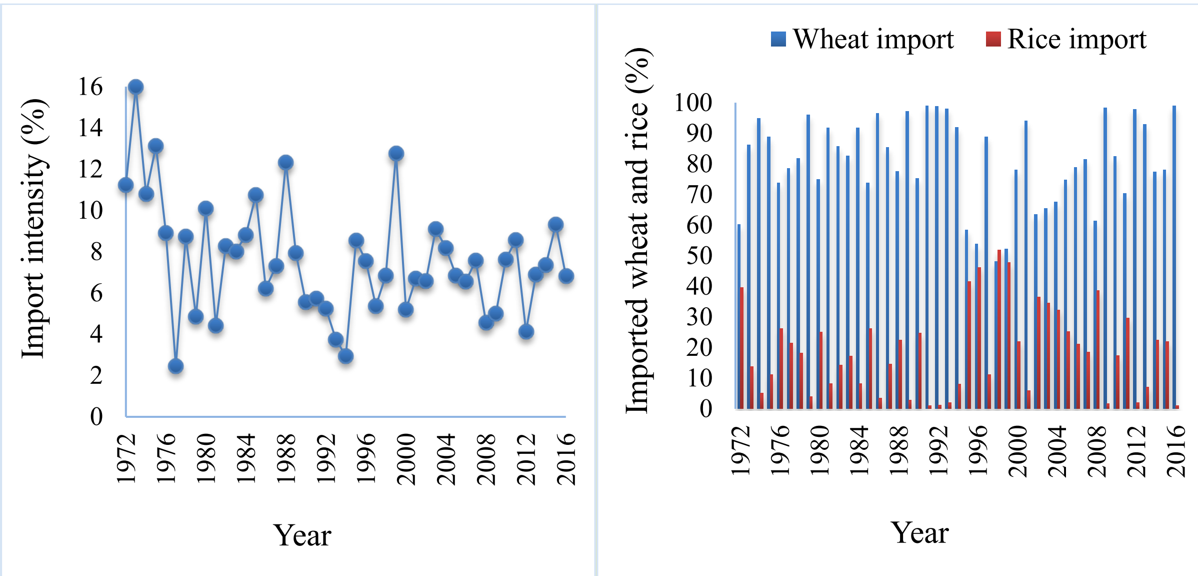
Sustainable Development Goal 2 (SDG2) adopted by the United Nations (UN) in 2015 envisions zero hunger. More specifically, it "seeks sustainable solutions to end hunger in all its forms by 2030 and to achieve food security" and promises to "end hunger, achieve food security and improved nutrition and promote sustainable agriculture" (United Nations, 2015). Closely related to SDG2 is SDG6 that underscores the need for ensuring availability and sustainable water management. Target 6.4 specifically emphasizes increasing water-use efficiency across all sectors and sustainable withdrawals and supply of freshwater to address economic or physical water scarcity (Target 6b).

Growing populations and a dwindling supply of arable land per capita in densely populated countries especially those in South Asia warrant sustainable increase in agricultural production by, amongst others, minimizing food losses due to climate change related phenomena. However, year-to-year non-stationary climate pose a potent threat to agricultural crop production (Gourdji et al., 2015). Though anthropogenic warming of the planet has had an influence on many physical, biological and environmental systems (IPCC, 2007; 2014), agriculture is always considered the most vulnerable sector (Chauhan et al., 2005; De Costa et al., 2007; World Bank, 2011; 2013; Mani et al., 2018).

Wheat is highly susceptible to climate change, particularly to increased temperature, drought and humidity. Asseng et al. (2015) projected that an increase of 1°C in temperature was likely to decrease wheat yield globally by 6%. This predicted decrease in wheat yield might threaten global food security and increase the incidence world hunger. This calls for reducing agricultural crop losses by ameliorating the unreliable weather effects (Alauddin and Sarker, 2014; Hasan et al., 2016; Islam et al., 2017).

Bangladesh is one of the most vulnerable countries to climate change due to her unique physio-graphic and socio-economic characteristics (World Bank, 2013; Hasan et al., 2016; MoEF, 2017; Mani et al., 2018). Bangladesh has witnessed a higher incidence of recurrent natural hazards with tropical humid climate in recent decades (Rashid, 1991; Islam, 2009; Alamgir et al., 2015). IPCC (2007; 2014) projected that by 2050, Bangladesh will experience an average temperature rise by 1.4°C (±0.16°C). Despite no appreciable changes in total annual rainfall, number of days without any rain has been on the rise. This erratic and uneven pattern of rainfall is primarily responsible for extreme droughts and floods (Sarker et al., 2012). Bangladesh is likely to face an increased number of warmer days and heat waves, longer dry spells and higher drought risks. Rahman and Lateh (2016) reported that, of the 13 severe droughts that hit Bangladesh in the four decades to 2010, those that occurred since the 1990s may be related to climate change. Severity of these climatic events heavily damage crop production undermining overall agricultural production and economic growth. More specifically, it may expose the fragility of the state of food security in Bangladesh.

Bangladesh is predominantly an agro-based economy. En though the relative contribution of agriculture to Bangladesh's GDP decreased to less than a fifth over the years due to a significant expansion of industrial and service sectors, it still employs more than two-fifths of the total labour force (GoB, 2016). The performance of this sector significantly affects major macroeconomic objectives including employment, poverty alleviation, human resources development and food security. Of all cereal crops, wheat plays the second most important role of total foodgrain production by covering 488 thousand ha producing 1.355 million MT of grain in 2015-16 (GoB, 2016). However, this level of wheat output falls far short of the demand which had made Bangladesh highly dependent on wheat import. In 2016-17 wheat import stood at 5.4 million MT (GoB, 2017). The demand for wheat grows every year due to rising population and people's health awareness and its use in the bakery industry. A shift in consumers' dietary preferences underpins this growing demand. The glycemic index (a worldwide accepted index for measuring blood glucose release) of wheat (62 ± 3) is significantly lower than that of rice (73 ± 4) (Jenkins et al., 1981; Atkinson et al., 2008; Rozendaal et al., 2018). Therefore, a growing number of diabetic patients in Bangladesh (Biswas et al., 2016) are changing their food habits from rice to wheat typifying a trend similar to that in India (Amarasinghe et al., 2007). However, Bangladesh produces approximately 1.3 million MT (29%) of wheat domestically but consumes 4.5 million MT, costing in excess of US$ 700 million each year (CIMMYT, 2017). Figure 1(a) displays the import intensity, while 1(b) shows relative percentage of imported rice and wheat in total food grain import during 1972-2016. Bangladesh imported more than 10% of the total quantity of available food grains (rice + wheat) in the early 1970s compared to considerably < 10% during the last 15 years or so even though the population has more than doubled in the meantime. However, a characteristic feature of food grain import that is the volume of wheat import has been considerably higher than that of rice for the entire length of the time series except for 1998 when rice import marginally exceeded that of wheat.



(a) Import as a percentage of total domestic food grain (rice + wheat) production

(b) Imported wheat and rice as a percentage of total food grain (rice + wheat) import.

Fig. 1. Food grain import intensity and rice-wheat import relativity, Bangladesh, 1972-2016. *Source*: Compiled from various issues of Economic Review of Bangladesh.

Furthermore, excessive import dependence may not only strain Bangladesh's fragile balance of payments but also make her more vulnerable to food insecurity and undermine sustainable development (Dioume, 2015). Hence, reduction in import dependency and to meet the rising demand warrants a focus on augmenting domestic wheat production. However, wheat yield volatility risks achieving this goal strongly associated with unreliable weather effects due to changing climatic patterns.

Against this background, this study espouses two broad objectives. First it examines the sensitivity of wheat yield to climate change over time and across the key and significant wheat growing climatic zones using a 45-year period panel data. Second, it explores the implications for Bangladesh's prospects for achieving SDG2 (food security) and SDG6 (sustainable water management) by expanding wheat cultivation. This paper contributes to the existing literature in three important ways. First, it uses a richer dataset on both traditional (temperature and rainfall) and non-traditional (bright sunshine and relative humidity) climate variables to assess their effects on wheat yield. Second, it uses an innovative analytical framework which can be adapted to other countries having similar bio-physical characteristics. Finally, the study explores policy implications for augmenting wheat production compatible with sustainable water use (SGD 6) and food security (SGD 2).

The remainder of the paper is organized as follows. Section 2 describes trends in wheat production while Section 3 reviews the relevant literature. Section 4 is devoted to materials and methods. Section 5 analyses and discusses the empirical results. Section 6 presents summary of conclusions and explores policy implications of the study.

2. Trends in wheat production and nutritional status: An overview

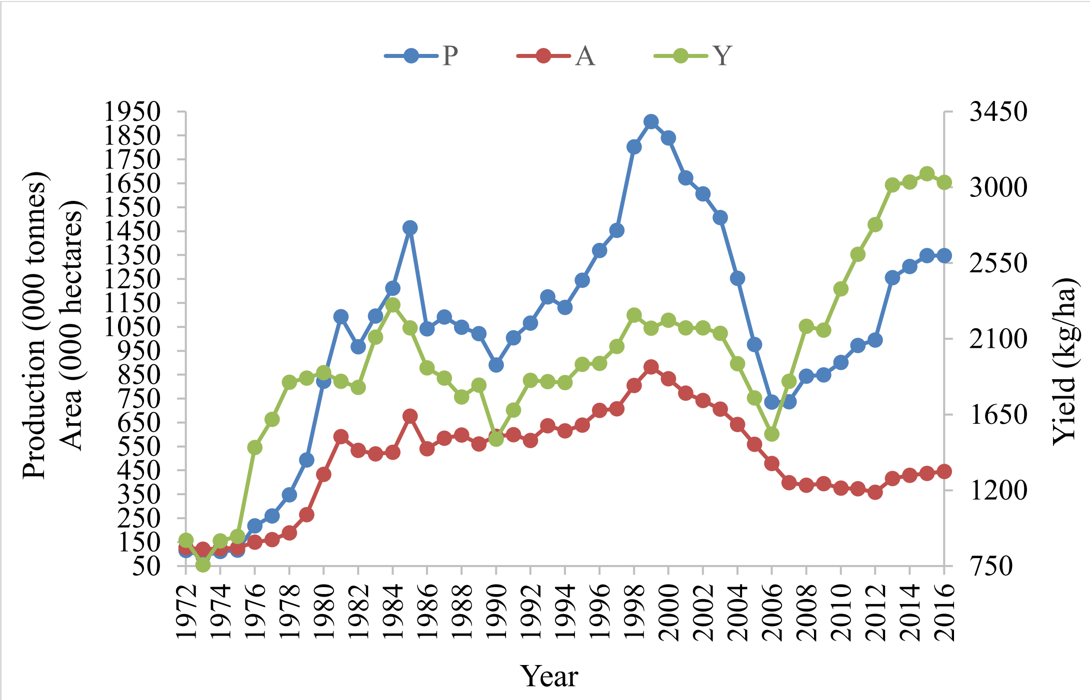
Aggregate wheat production in Bangladesh has increased over the years albeit with periodic fluctuations. Figure 2(a) presents wheat area, production and yield during the 1972-2016 period. Wheat yield portrayed in the right vertical axis typifies similar vulnerability. The highest national average wheat yield of 3,080 kg/ha was recorded in 2015, the second highest being 2,302 kg/ha in 1984.

Immediately after the independence in 1971, wheat production was sluggish because of post-war shocks and natural disasters as well as due a low level of cultural and social acceptability (Ahmed and Meisner, 1996). It gained momentum in the early 1980s. Furthermore, wheat production increased dramatically due to the adoption of green revolution technologies during 1990s (Alauddin and Hossain, 2001) albeit from a very low base. After reaching a peak production level of 1,908 thousand MT and cultivated area of 882 thousand ha in 1999, both fell sharply due to loss of cultivated land and wheat blast epidemic (BARI, 2017) before reaching their lowest levels in 2006. Since 2007 production has increased significantly to around 1,348 thousand MT of late while area under cultivation remained steady around 400-450 thousand ha. This typifies a shift in wheat cultivation from a largely area-based phenomenon to a yield-based one in earlier decades.

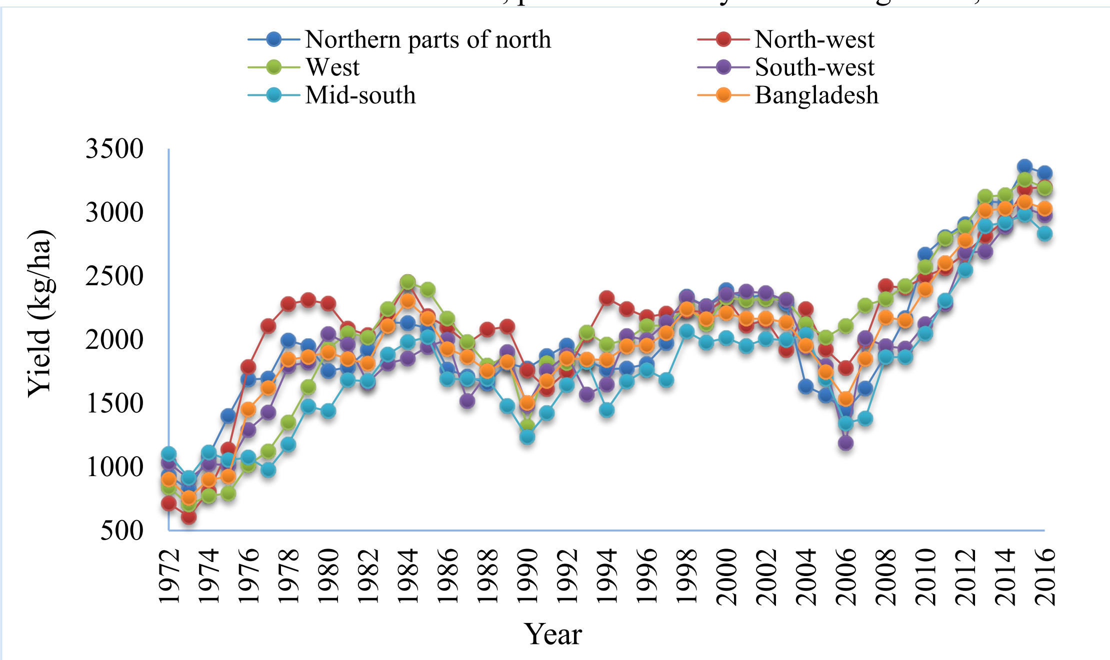
Figure 2(b) presents time patterns of wheat yields for Bangladesh and the five major wheat growing regions to put it in a comparative perspective. A closer inspection of the information contained in Figure 2(b) suggests that regions display broadly similar time patterns to that for Bangladesh as a whole even though interregional differences in magnitudes exist.

Information underlying Figure 2 (Panel A and Panel B) indicates five episodic patterns that broadly correspond to the following sub-periods:

1. 1972 - 1980: Early green revolution phase
2. 1981 - 1990: Early expanding phase
3. 1991 - 1999: Advance expanding phase
4. 2000 - 2006: Declining phase
5. 2007 - 2016: Research-led recovery phase



Panel A: Trends in wheat cultivation area, production and yield in Bangladesh, 1972-2016.



Panel B: Trends in wheat yields in a comparative perspective: Bangladesh and the five major wheat producing climatic zones, 1972-2016 (see Table 2 and Section 4 below).

Fig. 2: Trends in wheat area, yield and output for Bangladesh and yield trends in regional and national contexts, 1972-2016.

Source: Based on data from various issues of Economic Review of Bangladesh.

Table 1 summarises the salient features of growth and change in wheat cultivation for Bangladesh as a whole according to the above five episodes. Relative to Phase 1 wheat output increased by 324% and 372% respectively during Phase 2 (1981-1990) and Phase 3 (1991-1999). The increment declined to 272% during Phase 4 (2000-2006) before rising to 310% in Phase 5 (2007-2016). After increasing by 26% during Phase 2, relative to Phase 1, average wheat yield registered marginal increase during Phase 3 and Phase 4. In contrast, Phase 5 experienced a significant increase in yield by 73% over the one during Phase 1. Wheat output increase during the pre-2007 period resulted primarily from expansion in area while it is yield increase since 2007 was the dominant source of output growth. Scientific breakthroughs in wheat research in the last two decades may have underpinned this turning point. The varieties released by the Wheat Research and Bangladesh Agricultural Research Institute possess pest and disease resistance and drought tolerant characteristics hence risk and uncertainty reducing. Both output and yield appear to be more stable during Phase 5 at higher levels as indicated by their respective coefficients of variation.

Before 1998 different local and international varieties of wheat such as *Sonora* 64, *Kalyansona*, Sonalika *Ananda*, *Kanchan*, *Barkat* and *Akba*r were cultivated almost all over Bangladesh (Ahmed and Meisner, 1996). However since the mid-1990s and onwards, several new high yielding varieties (HYVs) have been released for adoption by farmers in the face of climate change (http://baritechnology.org/en/home/tech_commodity#result). Among these new varieties BARI *Gom 30,* BARI *Gom 24 (Prodip),* BARI *Gom 23 (Bijoy)* are now widely cultivated by farmers in all wheat growing regions. It is noteworthy that BARI *Gom* 33 developed in 2017 is more heat-tolerant while at the same time being high yielding. However, it is too early to be widely adopted by farmers.

Table 1: Salient features of growth and change in wheat output (000 MT), area (000 ha) and yield (kg/ha) by sub-periods, Bangladesh, 1972-2016

Sub-period	Sub-period average			% change over 1972-1980			Coefficient of variation (%)		
	Output	Area	Yield	Output	Area	Yield	Output	Area	Yield
1972-1980 (Phase 1)	286	188	1,521	-	-	-	84.4	54.6	31.4
1981-1990 (Phase 2)	1,213	636	1,909	324	238	26	12.8	26.0	24.7
1991-1999 (Phase 3)	1,351	684	1,973	372	264	30	23.7	27.0	20.3
2000-2006 (Phase 4)	1,066	526	2,026	272	179	33	37.5	35.8	17.0
2007-2016 (Phase 5)	1,173	447	2,626	310	137	73	20.0	40.6	9.4

Source: Derived from information contained in Figure 2.

Figure 3 illustrates Bangladesh's wheat yield in a comparative perspective with the World, South Asia, India and Pakistan averages for the corresponding years from 1972 to 2016. Except for 1979, 1980 and 1984 the world average wheat yield has remained above that of Bangladesh. For the entire period, the world average wheat yield has been about 25% above that for Bangladesh. Bangladesh's average wheat yield has remained consistently above that of the South Asian average during 1976-1985 and since 2013. The entire period average wheat yield for South Asia is only marginally (3.7%) above that for Bangladesh while those for India and Pakistan lie respectively 14.9% and 2.8% above. The Pakistani and Indian averages of wheat yields vis-a-vis the Bangladesh average follow a time pattern similar to the South Asian average.

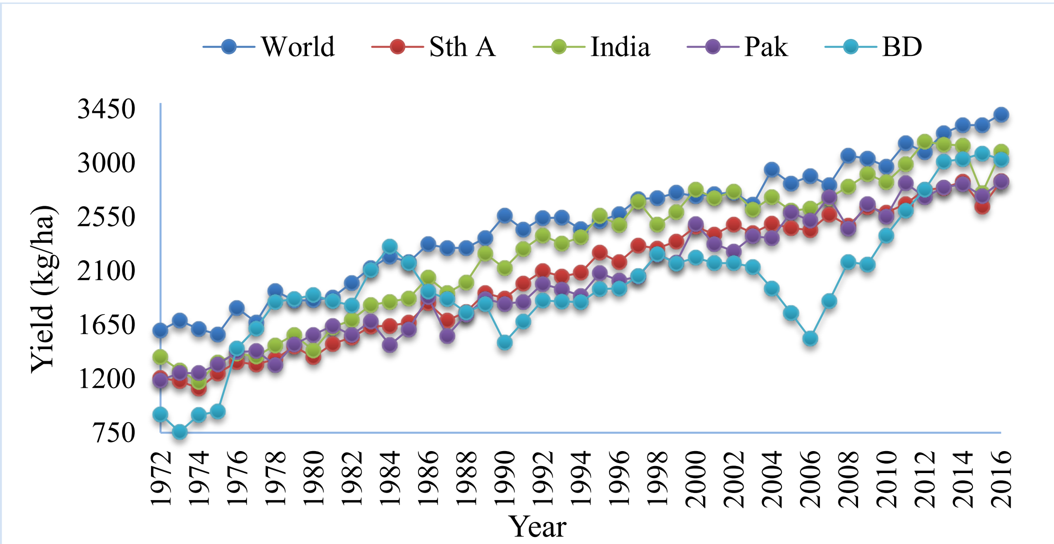


Fig. 3. Bangladesh wheat yield in a comparative perspective with the World, South Asia, India and Pakistan averages, 1972-2016.

Source: Based on data from various issues of Economic Review of Bangladesh; and FAOSTAT.

Bangladesh's high poverty and undernutrition rates are exacerbated by frequency and severity of natural disasters and high population density. Bangladesh has suffered an estimated financial loss of approx. US$ 2.3 billion from natural disasters including floods, cyclones, river erosion, and droughts respectively accounting for crops (36.2%) livestock (4.76% and land (26.72%) of the total damages during the 2009-2014 period (BBS, 2015).

Number of undernourished people stood at 24 million in 2014-16 (FAO, IFAD, UNICEF, WFP and WHO, 2017), a decline from 26.5 million in 2010-2012 (FAO, IFAD and WFP, 2015). However, a significant decline of 27% can be noted from the 1990-92 figure of 36 million (FAO, IFAD and WFP, 2015). Even though rates of undernourishment in Bangladesh are so high, a declining trend, albeit marginal, from 16.6% in 2004-06 to 15.1% in 2014-2016 can be observed (FAO, IFAD, UNICEF, WFP and WHO, 2017). Besides, Bangladesh graduated to the third quartile country (136/189, i.e., above 28% of countries) in 2018 from its 4th quartile ranking (129/169, i.e., above 23.7% of countries) in 2010 Human Development Index (HDI) (UNDP, 2016, i.e., 14.1% of countries). This epitomizes Bangladesh's steady progress in HDI to 0.608 in 2018 from 0.545 in 2010, 0.468 in 2000 and 0.386 in 1990 (UNDP, 2017) over a period of 28 years since 1990. Moreover, Bangladesh transitioned to 3rd quartile (88/119, i.e., above 26.1% of countries) in 2017 from 4th quartile (68/79, above i.e., 14.1% of countries) in 2012 in Global Hunger Index (GHI). These improvements notwithstanding Bangladesh struggles with hunger indicators in the serious range of 24.2 in 2010 to 27.3 in 2015 (IFPRI, 2017).

3. Review of Literature

A substantial body of research has assessed the impacts of climate change on wheat production in a global context. Studies assessing long-term yield responses to climate change have used growing season temperature, precipitation, and solar radiation. Wheat yield declines with warmer temperature (Hawker and Jenner, 1993; Jenner, 1994; Stone and Nicolas, 1994; 1995a, b; Yang et al., 2002; Shah and Paulsen, 2003; Wollenweber et al., 2003; Spiertz et al., 2006; Zhao et al., 2007; Asseng et al., 2015). Studies using simulation models have also reported similar findings for Australia (Gifford et al., 1998; Godden et al., 1998; Asseng et al., 2011; Luo et al., 2018); China (Yang et al., 2017); and Denmark (Patil et al., 2012; Ozturk et al., 2017). However, Fischer and Maurero, (1976), and Rane and Nagarajan, (2004) found wheat yield to be less sensitive to temperature variation. Among the conducted works most identified the precipitation as a risk-decreasing climate factor (see e.g., Turner and Asseng, 2005; Yu et al., 2014). Solar radiation appears to be an impediment to realizing wheat yield potential in Spain and Mexico (Villegas et al., 2016); Hernández-Barrera and Rodríguez-Puebla, 2017). Sommer et al. (2013) while investigating the impacts of climate change on wheat production in four Central Asian countries (Kazakhastan, Kyrgystan, Uzbekistan, and Tajikistan) employing CropSyst model found that increase in temperature had a significantly positive impact on wheat yield.

Research on the impact of climate change and cereal production in the Bangladesh context has paid inadequate attention to climate-wheat relationship. Hossain and Da Silva (2013) reported a negative relationship between wheat yield and heat stress. However, this study was not based on any rigorous statistical analysis but on observations and reviews of past studies. Miah et al. (2014) found that most climate variables (temperature and rainfall) had a significant impact on the income of wheat producers. Increasing temperature was found to decrease net revenue while the opposite was the case with rainfall. Jahan et al. (2018) reported that sowing date was a crucial determinant of wheat yield. When sown between 1 December to 20 December, on an average, grain yield of wheat was found to decrease by 30–40 kg day^{-1} ha^{-1} while early sowing (21 October–14 November) reduced grain yield by 102–148 kg day^{-1} ha^{-1}.

Schlenker and Roberts (2008) found that wheat yield response from small changes in climate variables was inadequate to find the exact nature of adverse effects using these simulation models. Amin et al. (2015) is the only study to use an empirical model for climate-crop relationships including wheat in Bangladesh. Their findings indicated no significant effect of climate variables except maximum temperature which had a negative impact on wheat yield. While Amin et al. (2015) provided useful information by using econometric technique, the study suffers from several limitations. First, the study used national level aggregate data masking regional patterns. Second, they used total rainfall growing season data rendering them inadequate for growing stage-specific (planting, flowering, harvesting) impacts of rainfall on wheat yield. Third, Amin et al. (2015) ignored the role of seasonal dry days when the West climatic zone (E) is a severely drought-prone area and groundwater depleted area (Alauddin and Sharma, 2013; Alauddin and Sarker, 2014; Rahman and Lateh, 2016) even though it is a key wheat growing region of Bangladesh (GoB, 2016).

As this is the first study of its kind for Bangladesh, this research epitomizes novelty in analyzing the stage-specific rainfall impacts on wheat yield when it is mostly a rain-fed crop, and defines total number of dry days of growing period to investigate long dry spell that may be associated with drought-related crop yield declines and losses. The primary objective of this study is to assess the impact of climate change on wheat yield in Bangladesh. In doing so, climate trends are firstly analyzed by using a linear trend model over 45 years (1972-2016) of climate data for the major wheat growing areas. A regression model is then employed to the panel data to estimate the effect of climate trends on wheat yield.

4. Materials and Methods

4.1. Major wheat growing areas, their physiographic characteristics and relative significance

Bangladesh is divided into seven major climatic regions: South-east (A), North-east (B), Northern parts of north (C), North-west (D), West (E), South-west (F) and Mid-south (G) (Figure 4). Table 2 presents the physiographic characteristics, and wheat cultivation in each of them and their relative significance in the national context.

South-east (A) and North-east (B) with 30% of Bangladesh's geographical area produce less than 0.6% of wheat output. Northern parts of north (C), North-west (D), and West (E) are the key wheat growing areas with a combined output share of 77% in 2016-2017. West (E) is the most wheat intensive region with 5.3% of Bangladesh's land area producing 21.2% of the national wheat output. This is followed by Northern parts of north (C) and North-west (D) with 9% and 13.6% of Bangladesh's area respectively produced 30.4% and 25.3% of national wheat output in 2016-2017. The three key wheat growing areas apart, South-west (F, 13.4%) and Mid-south region (G, 9.1%) are significant wheat producing areas with a combined national output share of 22.5%. Given the negligible contributions of South-east (A) and North-east (B) zones, they are excluded the econometric analysis undertaken in Section 5.

Table 2: Climate zone-specific physio-graphic characteristics of major wheat growing areas of Bangladesh

Area 000 km^2 (% Bangladesh)	2016-17 Wheat area, 000 ha (% Bangladesh)	2016-17 Wheat output, 000 MT (% Bangladesh [yield, kg/ha]	Soil type, climatic features, wheat season mean rainfall (mm), major crop suitability
South-east (A)			
32.7 (22.7)	Negligible	Negligible	Soil type: Grey, heavy silty clay loams, clays Climate features: Heavy rainfall, small range of mean temperature Wheat season mean rainfall (mm): 272 Major crop suitability: Rice, maize
North-east (B)			
10.1 (7.0)	Negligible	Negligible	Soil type: Grey silt loams, silty clay loam, friable loamy Climate features: Mild summer temperatures, heavy rainfall, cloudy cold winter Wheat season mean rainfall (mm): 575 Major crop suitability: Rice, potato
Northern parts of north (C)			
12.9 (9.0)	120.5 (29.0)	398.5 (30.4) [3,308]	Soil type: Sandy and silt Climate features: Very dry summer, very wet monsoon Wheat season mean rainfall (mm): 170 Major crop suitability: Rice, wheat, maize, potato
North-west (D)			
19.5 (13.6)	103.8(25.0)	332.0 (25.3) [3,200]	Soil type: Silty clay loam and sandy Climate features: Hot summer, moderate rainfall Wheat season mean rainfall (mm): 127 Major crop suitability: Rice, wheat, potato
West (E)			
7.5 (5.3)	86.9(20.9)	277.4 (21.2) [2.978]	Soil type: Clay with clay-loamy Climate features: Very hot summer, low rainfall Wheat season mean rainfall (mm): 108 Major crop suitability: Rice, wheat, potato
South-west (F)			
17.4 (12.1)	59.1(14.2)	175.9 (13.4) [3,191]	Soil type: Grey, silty clays Climate features: Hot summer, fairly heavy rainfall Wheat season mean rainfall (mm): 204 Major crop suitability: Rice, wheat
Mid-south (G)			
43.6 (30.3)	42.1 (10.1)	119.5 (9.1) [2,835]	Soil type: Friable clay loams, heavy silty clays Climate features: Mild summers and fairly heavy rainfall Wheat season mean rainfall (mm): 266 Major crop suitability: Rice, wheat, maize, potato

Source: Based on information from Rashid (1991), Alauddin and Hossain (2001), and GoB (2017).

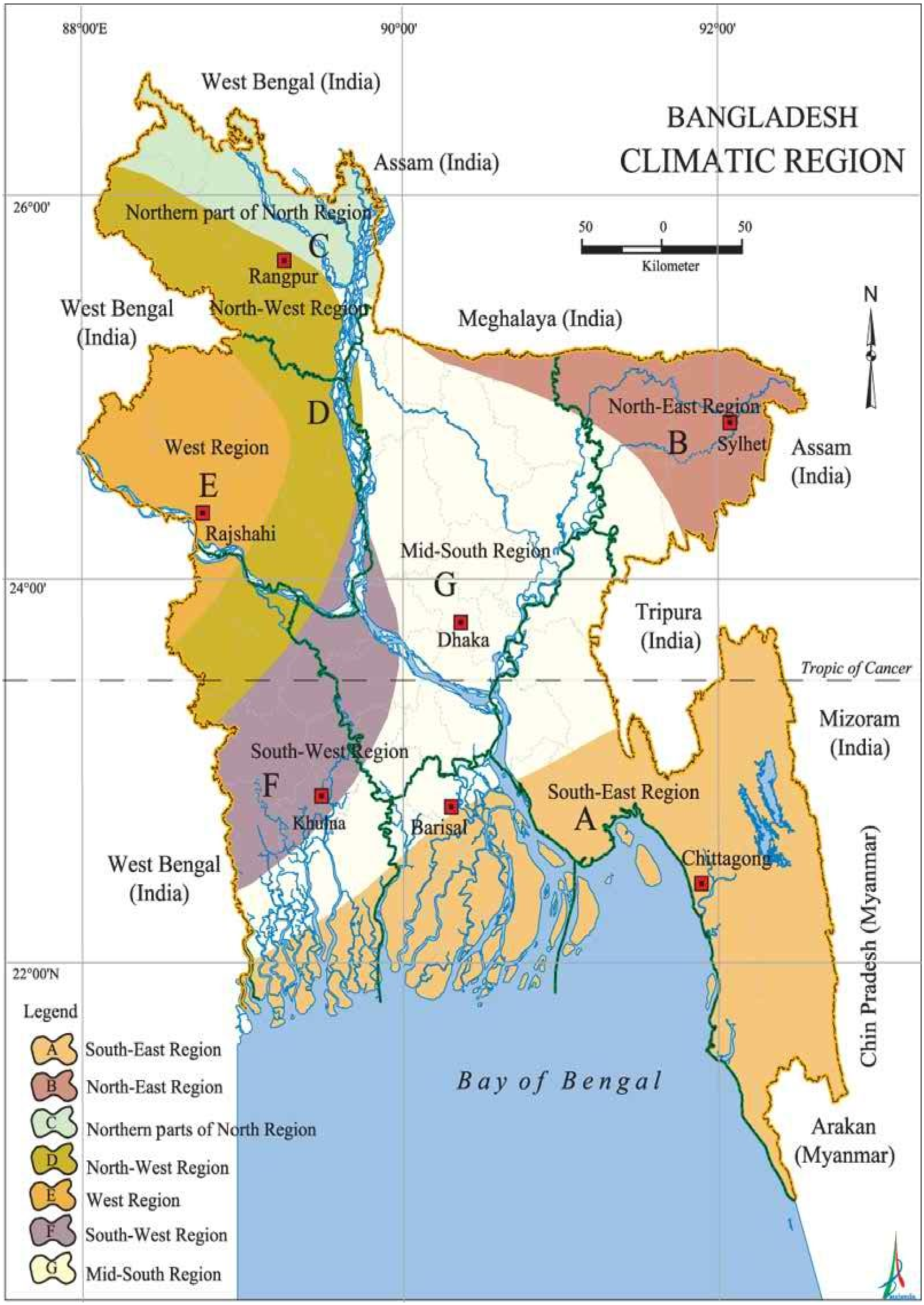


Fig. 4. Climate region-specified map of Bangladesh.
Source: Banglapedia (http://en.banglapedia.org/index.php?title=Climate).

4.2. Datasets and the phenology of wheat

The year-wise monthly weather datasets: average maximum temperature (°C), average minimum temperature (°C), total rainfall (mm), average bright sunshine (hours), and average relative humidity (%) were collected from Bangladesh Meteorological Department. This study also used daily records of rainfall to determine the number of days without rain during the wheat growing season. These historical meteorological data from 1972 to 2016 are employed to assess climatic trends. The year-wise monthly temperature (maximum and minimum) variables are firstly transformed into monthly average temperature (average of the monthly average maximum temperature and monthly average minimum temperature), and monthly temperature range (difference between monthly average maximum temperature and monthly average minimum temperature). Then, monthly average temperature and monthly temperature range are converted to seasonal average along with monthly average bright sunshine and monthly average relative humidity. However, year-wise monthly rainfall was estimated for seasonal total. The rainfall data were divided into three parts (planting time, flowering time, and harvesting time) to capture the definite rainfall effects. According to wheat growing season, these present study uses two calendar years. The planting period November and December are for previous year and January – April for the following year. Data on wheat yield (kg/ha) were available from the various issues of Yearbook of Agricultural Statistics of Bangladesh from 1972 to 2016.

The summary statistics of wheat yield and climate variables are reported in Table 3. The variations in all three rainfall variables are more noticeable than those in other variables.

Table 3: Descriptive statistics of the selected variables for major wheat growing climatic zones and Bangladesh, 1972-2016

Region	Maximum	Minimum	Mean	Standard deviation	Coefficient of variation
		Wheat yield (kg/ha)			
Northern parts of north (C)	3360	761	2012	562	27.93
North-west (D)	3200	608	2109.	532	25.21
West (E)	3258	631	2048	629	30.70
South-west (F)	3035	905	1927	502	26.09
Mid-south (G)	2981	646	1767	511	28.90
Bangladesh	**3080**	**757**	**1975**	**529**	**26.79**
		Average temperature (^{0}C)			
Northern parts of north (C)	22.92	20.6	21.62	0.45	2.08
North-west (D)	24.79	22.70	23.75	0.54	2.27
West (E)	23.95	21.70	22.60	0.48	2.12
South-west (F)	22.8	19.36	21.47	0.56	2.61
Mid-south (G)	24.47	21.44	22.58	0.67	2.97
Bangladesh	**24.79**	**19.36**	**22.40**	**0.99**	**4.42**
		Temperature range (^{0}C)			
Northern parts of north (C)	14.78	11.38	12.95	0.88	6.79
North-west (D)	13.84	9.90	11.88	0.78	6.56
West (E)	15.25	11.88	13.50	0.81	6.00
South-west (F)	13.87	8.86	12.05	1.00	8.30
Mid-south (G)	12.91	10.7	11.78	0.56	4.75
Bangladesh	**15.25**	**8.86**	**12.43**	**1.06**	**8.53**
		Planting rainfall (mm)			
Northern parts of north (C)	106	0	14.24	22.78	159.97
North-west (D)	169	0	38.17	49.86	130.63
West (E)	102	0	21.12	28.17	133.38
South-west (F)	112	0	15.51	22.61	145.78
Mid-south (G)	202	0	35.87	44.47	123.98
Bangladesh	**202**	**0**	**24.98**	**36.55**	**146.32**
		Flowering rainfall (mm)			
Northern parts of north (C)	74	0	17.73	17.38	98.03
North-west (D)	216	0	44.31	50.53	114.04
West (E)	120	0	23.17	22.70	97.97
South-west (F)	58	0	18.03	15.92	88.30
Mid-south (G)	181	0	35.78	36.29	101.43
Bangladesh	**216**	**0**	**27.81**	**32.87**	**118.19**
		Harvesting rainfall (mm)			
Northern parts of north (C)	204	1	76.14	55.60	73.02
North-west (D)	567	2	121.48	102.05	84.01
West (E)	266	7	82.29	62.10	75.46
South-west (F)	375	2	136.29	81.80	60.02
Mid-south (G)	951	177	503.02	219.26	43.59
Bangladesh	**951**	**1**	**183.84**	**200.64**	**109.14**
		Seasonal dry days (no. of days)			
Northern parts of north (C)	179	158	168.73	5.06	3.00
North-west (D)	175	146	164.41	5.87	3.57
West (E)	177	155	167.31	5.47	3.27
South-west (F)	176	107	162.78	14.55	8.94
Mid-south (G)	165	127	149.63	8.82	5.89
Bangladesh	**179**	**107**	**162.57**	**10.99**	**6.76**

Table 3 continued…

Region	Maximum	Minimum	Mean	Standard deviation	Coefficient of variation
		Bright sunshine (hours per day)			
Northern parts of north (C)	8.1	6.27	7.06	0.37	5.24
North-west (D)	8.74	5.77	7.88	0.51	6.47
West (E)	8.7	6.67	7.75	0.44	5.68
South-west (F)	9.0	5.16	7.29	0.69	9.47
Mid-south (G)	9.28	4.67	7.55	0.86	11.39
Bangladesh	**9.28**	**4.67**	**7.51**	**0.67**	**8.92**
		Relative humidity (%)			
Northern parts of north (C)	81	60.50	70.74	5.77	8.16
North-west (D)	80.34	67.50	75.55	3.16	4.18
West (E)	78	60.50	70.77	4.30	6.08
South-west (F)	90.16	62.66	76.88	4.61	6.00
Mid-south (G)	77.16	67.50	72.62	2.43	3.35
Bangladesh	**90.16**	**60.50**	**73.32**	**4.87**	**6.64**

Source: Based on data from Bangladesh Economic Review and Bangladesh Meteorological Department.

Four distinct climatic seasons can be recognized: dry winter (December-February), pre-monsoon (March-May), monsoon (June-September), and post-monsoon (October-November). The crop-growing period in Bangladesh is divided into pre-*kharif* (March-May), *kharif* (May-October), and *rabi* (November-February). *Rabi* season covers the months with little or no rainfall. Wheat is mainly a *rabi* crop which grows during dry season (November to mid-April). Moreover, this crop cultivation depends partly on rainfall and partly on groundwater irrigation. Based on GoB (2016) the phenology of what cultivation suggest that sowing, flowering and harvesting respectively take place during November-December, January February and March-mid April.

4.3. Regression model specification

We define a regression model for cross-sectional time series of regional yield and weather data in the wheat producing areas as follows:

$$ln\,\text{yield}_{it} = \beta_0 + \beta_1\text{average temperature}_{it} + \beta_2\text{temperature range}_{it} +$$

$$\beta_3\text{palnting rainfall}_{it} + \beta_4\text{flowering rainfall}_{it} + \beta_5\text{harvesting rainfall}_{it} +$$

$$\beta_6\text{seasonal dry days}_{it} + \beta_7\text{bright sunshine}_{it} + \beta_8\text{relative humidity}_{it} + \beta_9\text{trend}_{it} +$$

$$\beta_{10}\text{time dummy } (1981-2006)_t + \beta_{11}\text{time dummy } (2007-2016)_t +$$

$$\beta_{12}\text{northern parts of north}_i + \beta_{13}\text{north west}_i + \beta_{14}\text{west}_i + \beta_{15}\text{south west}_i + \varepsilon_{it}$$

Where,
i = Northern parts of north, north-west, west, south-west
t = Time dummy (1981-2006 = 1, 0 otherwise), time dummy (2007-2016 = 1, 0 otherwise)
β = intercept
ε = random disturbance term

This study employs a fixed effect model instead of a random effect model in order to highlight issues of regional differences and the possibility of correlation between regressors and time-invariant distinctiveness (Sarker et al., 2014), as is the case here. In addition to weather variables, time trend by year term, and regional dummies are also included in the model. However, four regional dummies for five regions are used to avoid dummy variable trap. The two time trend dummies attempt to capture technological progress while regional dummies characterize the estimation of relatively static soil and management differences across the regions in the mean yield function. Finally, a three-stage feasible generalized least squares (FGLS) method is run in preference to maximum likelihood estimation (MLE) to estimate the fixed effect panel model because of large sample size (N = 225).

5. Results and Discussion

5.1. Climate trends

Table 4 reports significant trends in climate variables for major wheat growing regions of Bangladesh. Trends in harvesting rainfall and temperature are not statistically significant and are not reported for brevity. The wheat growing season has witnessed warmer temperatures in all wheat growing areas except the South-west (F). Rising temperature affected 85% of the wheat growing areas in Bangladesh. Significant declining trends can be observed in rainfall during planting and flowering periods in Northern parts of the north (C), Northwest (D) and West (E) affecting three-quarters of the total wheat growing area in Bangladesh. This underscores the need for supplementary irrigation for wheat cultivation. Number of seasonal dry days has shown an increasing trend in regions C, D and E. The increasing number of dry days may be associated with drier weather for cultivated areas facing drought related risk. Bright sunshine demonstrates a downward trend only in the Southwest (F) which has 14% of the wheat area of Bangladesh. Relative humidity exhibits a significant upward trend only in the Northwest (D) with 25% of the total wheat growing area of Bangladesh. Overall, a widespread variations in climate patterns during wheat growing season across regions exist.

5.2. Data stationarity

Unit root test exploits both time series and cross-sectional dimension of the data. The Fisher-type Augmented Dickey-Fuller (ADF) test and subsequently Harris-Tzavalis (HT) test for the assurance of robustness have been widely used to examine the stationarity. These results are reported in Table 5. Test statistics from both tests reject the null hypothesis of all panels containing unit roots implying non-stationarity ($p<0.01$). These results are consistent with McCarl et al. (2008), Kim and Pang (2009), and Sarker et al. (2014). Therefore, no co-integration causality tests are executed before using three-stage feasible generalized least squares method.

Table 5: Significant time trends in climate variables for major wheat growing regions and Bangladesh, 1972-2016

Region	*Trend*	*p*-value
Average temperature		
Northern parts of the north (C)	0.19***	0.002
Northwest (D)	0.08***	0.001
West (E)	0.04***	0.004
South-west (F)	0.08	0.102
Mid-south (G)	0.38**	0.024
Bangladesh	0.05***	0.001
Planting rainfall		
Northern parts of the north (C)	-0.06**	0.026
Northwest (D)	-0.37**	0.043
West (E)	-0.12**	0.032
South-west (F)	-0.21	0.122
Mid-south (G)	-0.29	0.426
Bangladesh	-0.13**	0.011
Flowering rainfall		
Northern parts of the north (C)	-0.13**	0.014
Northwest (D)	-0.17**	0.021
West (E)	-0.05**	0.043
South-west (F)	-0.14	0.146
Mid-south (G)	0.28	0.917
Bangladesh	-0.01**	0.024
Seasonal dry days		
Northern parts of the north (C)	0.06**	0.012
Northwest (D)	0.16***	0.006
West (E)	0.07***	0.001
South-west (F)	0.39	0.242
Mid-south (G)	0.18	0.323
Bangladesh	0.02***	0.003
Bright sunshine		
Northern parts of the north (C)	-0.07	0.495
Northwest (D)	-0.08	0.413
West (E)	-0.10	0.353
South-west (F)	-0.03**	0.019
Mid-south (G)	0.04	0.541
Bangladesh	-0.06**	0.045
Relative humidity		
Northern parts of the north (C)	0.35	0.372
Northwest (D)	0.14***	0.009
West (E)	0.28	0.214
South-west (F)	0.01	0.287
Mid-south (G)	0.03	0.288
Bangladesh	0.38	0.726

Note: Temperature range and harvesting rainfall did not show any significant trend in any of the climatic zones and are not reported.. $^{**}p < .05$; $^{***}p < .01$.

Table 5: Data stationarity tests

Variable	ADF test statistic (*p*-value)		HT test statistic (*p*-value)	
	without trend	with trend	without trend	with trend
wheat yield	53.57 (0.000)	43.67 (0.000)	0.76 (0.000)	0.64 (0.000)
average temperature	31.30 (0.000)	34.56 (0.000)	0.18 (0.000)	0.02 (0.000)
temperature range	37.90 (0.000)	36.78 (0.000)	0.43 (0.000)	0.33 (0.000)
planting rainfall	55.18 (0.000)	48.58 (0.000)	-0.14 (0.000)	-0.18 (0.000)
flowering rainfall	37.52 (0.000)	30.94 (0.000)	0.07 (0.000)	0.06 (0.000)
harvesting rainfall	50.32 (0.000)	44.72 (0.000)	-0.23 (0.000)	-0.26 (0.000)
seasonal dry days	44.05 (0.000)	45.30 (0.000)	0.02 (0.000)	-0.08 (0.000)
bright sunshine	63.99 (0.000)	85.69 (0.000)	0.58 (0.000)	0.28 (0.000)
relative humidity	85.67 (0.000)	89.07 (0.000)	0.61 (0.000)	0.40 (0.000)

Hypothesis under ADF test: H_0: All panels contain unit roots; H_1: At least one panel is stationary. Hypothesis under HT test: H_0: panels contain unit roots; H_1: panels are stationary.

5.3. Results of regression model

The estimated results are presented in Table 6. Overall the model appears to be satisfactory given an R^2 of 0.62 and a Wald χ^2 (78.97, p <0.01). Four climate variables significantly affect wheat yield. Wheat yield decreases with an increase in average temperature (p <0.01). Wheat yield varies directly with rainfall during both planting (p <0.05) and flowering (p <0.05) stages of the production cycle. Rainfall during planting phase has a stronger positive effect on wheat yield than flowering rainfall. On the other hand, an increase in the number of dry days results in a decline in wheat yield (p <0.01). Other climatic variables such as temperature range, harvesting rainfall, bright sunshine and relative humidity do not have any significant effect on wheat yield.

Wheat yield shows a significant positive time trend. The two time dummies (1981-2006) and (2007-2016) clearly demonstrate that wheat yield grew at significantly higher rates relative to the one for 1972-1980 (Phase 1). The coefficients of the two dummy variables (.03 for 1981-2007 and .16 for 2007-2016) measure the instantaneous (at a point of time) growth rates, not compound growth rates over a period of time. Following Gujarati (2003, p.180) compound growth rates can be found as [exp (coefficient) -1] x100. In the present case, the resulting annual compound growth rates for the 1981-2006 and 2007-2016 came to 3.05% and 17.35%

respectively. The spectacular yield growth during the last decade of the time series can be linked to the technological breakthrough in wheat research.

Wheat yield varied across climatic regions. Wheat yield in the South-west (F) was significantly lower (p <0.01) than that of the Mid-south (G) region while those in Northern parts of north (C, p <0.01) and West (E, p <0.01) were significantly higher. There does not appear to be any significant difference in yields between North-west (D) and Mid-south (F, p <0.14). Additionally, the South-west (F) region has significantly different yields than either of the rest regions, after accounting for climate variability. This could be due to persistent differences in agro-ecological conditions or management practices.

Table 6: Estimated model coefficients for wheat yield using panel data, 1972-2016.

	Coefficient	***p*-value**
Explanatory variable	**Dependent variable: *ln* wheat yield**	
Average temperature	-0.13***	0.003
Temperature range	0.03	0.527
Planting rainfall	0.06**	0.043
Flowering rainfall	0.04**	0.039
Harvesting rainfall	0.01	0.156
Seasonal dry days	-0.09***	0.002
Bright sunshine	0.02	0.417
Relative humidity	-0.09	0.461
Time trend	0.02***	0.000
Time dummy (1972-1980)	Reference period	
Time dummy (1981-2006)	0.03**	0.045
Time dummy (2007-2016)	0.16***	0.007
Northern parts of north (C)	0.07***	0.000
North-west (D)	0.02	0.144
West (E)	0.06***	0.000
South-west (F)	-0.04***	0.000
Mid-south (G)	Reference climatic region	
intercept	0.49	0.246
Model statistics		
N		225
R^2		0.62
Wald chi-square		78.97
p-value		0.000

**p < 0.05; and ***p < 0.01.

5.4. Climate elasticities of wheat yield

To measure the relative yield response to changes in statistically significant climatic variables we transform the coefficients of climate parameters into elasticities by multiplying them by the corresponding averages and dividing by average wheat yield (Chen et al., 2004; Sarker et al., 2013; 2014). Table 7 presents these elasticities while Figure 5 illustrates them.

Rise in the number of seasonal dry days and average temperature were the two variables that most adversely affected wheat yield. A 1% increase in seasonal dry days resulted in a .92% decrease in wheat yield while a 1% increase in average temperature was likely to lead to a 0.82% decline in wheat yield. However, both the planting and flowering rainfall had ameliorating effects on wheat yield. A 1% increase in each of these variables resulted in likely yield increases of 0.43% and 0.29% respectively.

Table 7: Climate elasticities of wheat yield for variables significant at $p < 0.05$

Climate parameter	Wheat yield elasticity
Seasonal dry days	-0.92
Average temperature	-0.82
Planting rainfall	0.43
Flowering rainfall	0.29

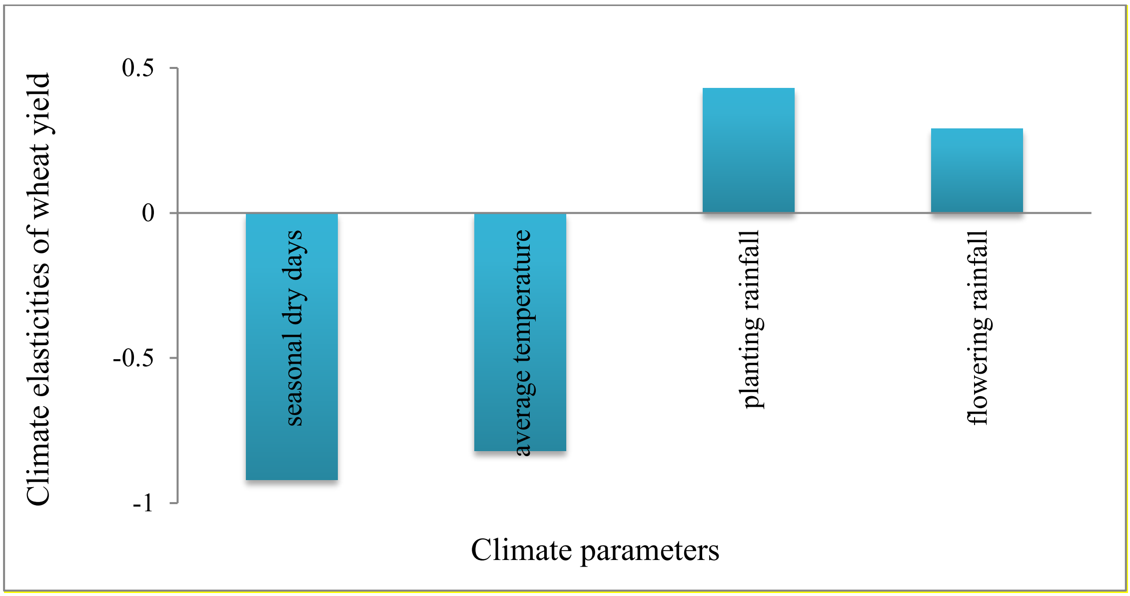


Fig. 5. Climate elasticity of wheat yield for significant climate variables

6. Exapanded wheat cultivation: Implications for food security (SDG2) and sustainable water management (SDG6)

In light of the preceding discussion, this section explores the prospects for expanded wheat cultivation and its implications for SDG2 and SDG6.

Key questions:

- What do the land suitability data suggest?
- To what extent onmentally To what extent

7. Conclusions and Policy Implications

7.1. Summary of conclusions

The study notes the effect of unremitting climate change on, a key staple crop, productivity in Bangladesh. A highly strong change in climatic trends mostly warmer temperature, less rainfall, and longer dry days has been observed by analysing the last 45 years historical weather records.

Results from the statistical model indicate that wheat yield has signifciantly declined due to the increase in average temperature, and number of dry days. It is also susceptible to relative humidity. The study at found rainfall at planting and flowering conducive to wheat yield.

Regional dummies are found to be statistically significant with non-climate related differential spatial impacts on wheat. This indicates that climate change affects different climate zones differently. Moreover, time trend shows technological advances which have likely mitigation options for some of these climate stresses on wheat yield.

6.2. Policy implications

The findings of this study recommend generating new wheat varieties that can withstand extreme hot weather conditions. In Bangladesh, though wheat production are damaged by heat stress and drought risk since several years, the progress on the development of heat and drought tolerant wheat varities are still unsatisfactory. However, Wheat Research Centre (WRC), one of the six research centres of Bangladesh Agricultural Research Institute (BARI), located at Nashipur in Dinajpur district has developed nine wheat varieties from January 2009 to December 2017 to overcome the adverse effects of climate change. The varities developed under the guidence of BARI are: BARI *Gom*-25 and BARI *Gom*-26 (released 2010); BARI *Gom*-27 and BARI *Gom*-28 (released 2012); BARI *Gom*-29 and BARI *Gom*-30 (released 2014); and BARI *Gom*-31 (2017), BARI *Gom*-32 and BARI *Gom*-33 (released 2017). All these varieties are high yielding and tolerant to terminal heat stress and resistant to stem rust diseases as well. But, these are unable to absolutely stand against heavy drought related environments. Hence, wheat research centres and organizations should focus on developing wheat virieties, those are highly adaptive to drought severity. It is thus essential to develop and introduce changing climate friendly wheat seed varities with better yielding capacity. Bangladesh government should allocate adequate funds for the state-run wheat research agencies. Both governmental and non-governmental organizations should play a more significant role in demonstrating and disseminating new wheat varieties among wheat farmers. It is because that the quicker use of newly developed high-yielding wheat varities that are temperature and drought-compatible along with better crop management technologies will increase wheat productivity, reduce the country's import dependence and ensure food security.

It is also noted that the South-west Bangladesh was strucked by wheat blast disease in a surprise outbreak on 15,000 ha of wheat area, which accounts for approximately 25-30% average yield losses (BARI, 2017). Using a breeding line from the International Maize and Wheat Improvement Center (CIMMYT), Bangladesh Wheat Research Centre (WRC) has released bio-fortified BARI *Gom*-33 in 2017 resilient to wheat blast disease. Now it is under experiment in the field trials in Bangladesh and Bolivia. Response is yet to be available (BARI, 2017). So, we need substantial improvements of wheat varieties to be tolerant to such kinds of epidemic diseases.

The use of chemical and fertilizer to control pest management is increasing day by day for wheat cultivation in Bangladesh (GoB, 2017). Massive use of chemical and fertilizer is costly and potentially harmful for human and environmental health. So, protecting wheat with inherent pest resistance is the smart alternative. Genetically complex new wheat varities combining several genes to withstand new mutation of the pathogen must immediately be released. Furthermore, scientists should try to invent less rain-water consuming wheat as it is rain-dependent crop to eliminate the unfavourable effect of decling rainfall trend over the years. For the erratic shifting seasonal period for rain-fed wheat, adding to small-scale supplementary water irrigation can greatly increase the production for farmer who traditionally relies on rainfed cultivation.

Given, many parts of Bangladesh is under the threat of severe groundwater depletation problem (Alauddin and Sarker, 2014), switching to surface water irrigation practices may be the best choice for sustainable wheat growth. Ground water extraction results high energy cost and health risk due to arsenic contamination in Bangladesh (Santos valle et al., 2014). In contrast, surface water deals with low energy and low carbon emissions (Santos valle et al., 2014). Axial Flow Pumps (AFPs) can be used for water use efficiency. Although, Bangladesh introduced with AFPs in 2013 (Santos valle et al., 2014), effort is not adequate to reach to local farmers. Thus, organizing comprehensive training programme for the native poor farmers will help to introduce and efficiently adopt with this technology.

In addition, agro-forestry and soil conservation measures can be helpful to mitigate the rising climate trends. More importantly, region specific research to emphasise regional differences should be undertaken, which indicates local or micro-level adaptation strategies could be very useful to confront uneven climate impacts. Finally, these policy recommendations, if practised well, will be able to help meeting Bangladesh's food security and achieving SDG2 and SDG6.

Wheat Research Centre (WRC) developed many varieties but detailed adoption information is not well documented though it is very imperative for the agricultural scientists and policy makers. Among the varieties, thirteen are adopted by farmers in the recent years and BARI Gom 24 (*Prodip*) covered the highest cultivated area with 41.03% of total wheat cultivated area. It is possibly because of its very attractive characteristics including high yield, big spike, large grain, and lodging tolerance. This was followed by BARI *Gom* 21 (*Shatabdi*), BARI *Gom* 26 and BARI Gom 23 (*Bijoy*) with respective percentage shares of 24.97%, 11.43% and 11.06% of the total area under wheat cultivation (Rashid and Hossain, 2016, p. 499). However, BARI *Gom* 30, 31, 32 and 33 (all released since 2014) are likely to be widely adopted given their heat stress, salinity and lodging-compatible attributes as well as being short maturing.

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Appendix Table 1: Salient features of wheat varieties developed by Wheat Research Centre (WRC) and Bangladesh Agricultural Research Institute (BARI) since 1998

Variety	Year of release	Yield (t/ha)	Maturity (days)	General attributes	Disease and pest tolerance level	Climate tolerance capacity
BARI Gom 19 (Sourav)	1998	3.5-4.5	102-110	A semi-dwarf short duration high yielding variety	Tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases, and major insects	High tolerance to lodging
BARI Gom 20 (Gourab)	1998	3.5-4.6	102-108	A semi-dwarf short duration high yielding variety	Tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases, and major insects	Tolerant to terminal heat stress
BARI Gom 21 (Shatabdi)	2000	3.6-5.0	105-110	A semi-dwarf variety with good tillering ability and high yield	Highly tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases	Tolerant to terminal heat stress
BARI Gom 22 (Sufi)	2005	3.6-5.0	105-110	A semi-dwarf variety with good tillering ability	Highly tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases, and resistant to major insects	Tolerant to late heat stress
BARI Gom 23 (Bijoy)	2005	4.3-5.0	103-112	A semi-dwarf variety with good tillering ability	Highly tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases; Resistant to major insects	Moderately heat tolerant
BARI Gom 24 (Prodip)	2005	4.3-5.1	102-110	A semi-dwarf with high yielding ability	Highly tolerant to *Bipolaris* leaf blight; Resistant to leaf rust diseases; Resistant to major insects	Heat tolerant
BARI Gom 25	2010	3.60-5.00	102-110	Grains are amber in colour, bright and larger in size	High tolerance to *Bipolaris* leaf blight; Resistant to leaf rust diseases	Moderate level heat stress tolerant; Salinity tolerant
BARI Gom 26	2010	3.50-5.00	104-110	Grains are amber in colour, bright and larger in size	Tolerant to *Bipolaris* leaf blight; Resistant to leaf rust, and stem rust race	Tolerant to terminal heat stress
BARI Gom 27	2012	3.50-5.40	105-110	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to stem race and leaf rust; Moderately resistant to *Bipolaris* leaf blight	Moderately tolerant to terminal heat stress
BARI Gom 28	2012	4.00-5.50	102-108	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to leaf rust; Moderately resistant to *Bipolaris* leaf blight	Highly tolerant to terminal heat stress due to its earliness
BARI Gom 29	2014	4.00-5.00	105-110	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to stem rust (race Ug99) and leaf rust; Tolerant to BpLB disease	Tolerant to lodging; Moderately tolerant to terminal heat stress
BARI Gom 30	2014	4.50-5.50	100-105	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to stem rust race, Ug 99 and leaf rust; Moderately resistant to *Bipolaris* leaf blight	Good tolerance level to terminal heat stress
BARI Gom 31	2017	4.50-5.00	105-109	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to leaf rust and *Bipolaris* leaf blight	Tolerant to terminal heat stress
BARI Gom 32	2017	4.60-5.00	95-105	High yielding and short stature; White amber colour grain, Medium grain size	Resistant to leaf rust and *Bipolaris* leaf blight; Tolerant to whEat blast	Tolerant to terminal heat stress
BARI Gom 33	2017	4.00-5.00	110-115	Shiny amber (whitish) colour; Medium grain size; Zn enriched (55-60 ppm)	Resistant to major diseases including wheat blast; Resistant to major insects	Heat tolerant

Source: Based on http://baritechnology.org/en/home/tech_commodity#result