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Climate change and crop farming in Bangladesh: an analysis of economic impacts

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Abstract

Purpose – Changes in climate may have both beneficial and harmful effects on crop yields. However, the effects will be more in countries whose economy depends on agriculture. This study aims to measure the economic impacts of climate change on crop farming in Bangladesh.

Design/methodology/approach – A Ricardian model was used to estimate the relationship between net crop income and climate variables. Historical climate data and farm household level data from all climatic zones of Bangladesh were collected for this purpose. A regression model was then developed of net crop

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income per hectare against long-term climate, household and farm variables. Marginal impacts of climate change and potential future impacts of projected climate scenarios on net crop incomes were also estimated.

Findings – The results revealed that net crop income in Bangladesh is sensitive to climate, particularly to seasonal temperature. A positive effect of temperature rise on net crop income was observed for the farms located in the areas having sufficient irrigation facilities. Estimated marginal impact suggests that 1 mm/month increase in rainfall and 10°C increase in temperature will lead to about US$4-15 increase in net crop income per hectare in Bangladesh. However, there will be significant seasonal and spatial variations in the impacts. The assessment of future impacts under climate change scenarios projected by Global Circulation Models indicated an increase in net crop income from US$25-84 per hectare in the country.

Research limitations/implications – The findings of this study indicate the need for development practitioners and policy planners to consider both the beneficial and harmful effects of climate change across different climatic zones while designing and implementing the adaptation policies in the country.

Originality/value – Literature survey of the Web of Science, Science Direct and Google Scholar indicates that this study is the first attempt to measure the economic impacts of climate change on overall crop farming sector in Bangladesh using an econometric model.

Keywords Bangladesh, Climate change, Adaptation, Crop farming, Net crop income, Ricardian model

Paper type Research paper

1. Introduction

Climate change and variability have human and non-human effects across the globe. Increasing temperatures, changing rainfall patterns, rising sea levels, and increasing frequency and intensity of extreme weather events are adversely affecting ecosystem functioning, agriculture and food security, infrastructure, water resources, and human health (Intergovernmental Panel on Climate Change (IPCC, 2014). However, there is considerable debate on how adverse effects of climate change will genuinely be in different parts of the world. Evidence suggests that developed countries located in temperate regions would face less adverse impacts and may gain from climate change (Mendelsohn and Dinar, 2003). In contrast, there is a scientific consensus that the non-industrialized and low-income nations located in tropical and sub-tropical climate are more prone to the negative impacts of climate change (Wheeler and Von Braun, 2013; Ruamsuke *et al.*, 2015).

Climate change will significantly affect crop productivity and efficiency and will lead to important changes in agricultural outcomes (IPCC, 2014; Arshad *et al.*, 2018). Moreover, extreme climatic events, soil salinity in coastal areas, and incidence of pests and diseases may result in additional adverse effects on agriculture sector (Rosenzweig *et al.*, 2001). Despite the technological advancement, the climate is still a fundamental determinant of agricultural productivity where temperature and rainfall act as primary drivers of crop production and by consequence rural food security (Wheeler and Von Braun, 2013). Increased crop yield under elevated carbon dioxide (CO_2) in the atmosphere would slightly offset some of the adverse effects of climate change but only in the short-term (Calzadilla *et al.*, 2013). Without accounting for CO_2 fertilization, it has been projected that climate change would cause a decrease in yield by 17 per cent for a number of crops in different regions across the world (Nelson *et al.*, 2014). Building on these issues, a number of studies have analyzed the farm household level present and potential future impacts of climate change on agricultural productivity, net farm incomes and farmland values (Mishra *et al.*, 2015; Arshad *et al.*, 2016; Van Passel *et al.*, 2016; Huong *et al.*, 2018).

Bangladesh is one of the most vulnerable countries in the world to climate risks and natural disasters (Agrawala *et al.*, 2003). The location of the country is in low-lying floodplains at the confluence of three mighty Asian rivers, the Brahmaputra, the Ganges and the Meghna along with their numerous tributaries (World Bank, 2010). Because of this natural geographic design, the country faces severe floods on a regular basis. The floods of 1974, 1984, 1987, 1988 and 1991 were most destructive and caused loss of human lives and serious damage to agricultural production (Agrawala *et al.*, 2003). Besides, its position between the funnel-shaped Bay of Bengal in the south and the world's highest mountain Himalayas in the north has made the country a place of intensive monsoon rainfalls, cyclones, floods, storm surges etc. (Ferdous and Baten, 2011). After the catastrophic cyclones of 1970 and 1991, cyclone Sidr of 2007, for example, was among the most devastating disasters in recent years. It caused a loss of 3,295 lives and destroyed approximately 1.5 million households and 2.2 million hectares of cropland. The total damage was estimated at about US$1.67bn (International Federation of Red Cross and Red Crescent Societies (IFRC, 2010). It has been projected that country will experience more frequent and natural disasters in near future due to climate change (IPCC, 2007).

A sharp rise in temperature and changes in rainfall patterns are already evident in Bangladesh (Shahid, 2010; Shahid *et al.*, 2012). The average daily temperature in Bangladesh has increased by 0.103°C per decade over the past four decades (Shahid, 2010). There have also been reports of changes in spatial variability and seasonal pattern in rainfall (Shahid and Khairulmaini, 2009). The projections say that temperature of Bangladesh will continue to increase by 1°C by 2030, 1.4°C by 2050 and 2.4°C by 2100 due to global warming (IPCC, 2007). Rising temperature will enhance evapotranspiration and air moisture holding capacity which in turn will change the annual and seasonal variability of rainfall and their spatial distributions. Such changes in climate can have severe impacts in an agro-based country like Bangladesh, where more than 55 per cent of the total population directly depends on agriculture, and 17.22 per cent of the gross domestic product (GDP) comes from this sector (Bangladesh Bureau of Statistics (BBS, 2015). Crop farming is the primary source of food for 149.77 million people and accountable for food security both in urban and rural populations (BBS, 2015).

Considering the vulnerability and sensitivity of Bangladeshi agriculture sector to climate change, this paper attempts to answer the important questions:

Q1. Does climate change affect net incomes from crop farming sector in Bangladesh?

Q2. Will crop farming in Bangladesh be profitable under future climate change scenarios?

Q3. What are the necessary steps for the government policy planners to minimize the negative impacts of climate change on crop farming?

However, to answer these questions, studies in this direction are still insufficient. Only a few studies have been conducted in recent years to assess the impact of climate change on agriculture in Bangladesh (Sarker *et al.*, 2012; Amin *et al.*, 2015; Chowdhury and Khan, 2015). Amin *et al.* (2015) reported the significant impact of different climate variables namely, temperature, rainfall, humidity, and sunshine on the yield of major food crops (rice and wheat). Sarker *et al.* (2012) studied the relationships among maximum temperature, minimum temperature, and rainfall with three varieties of rice crops and found a significant impact of climatic variables on the productivity of rice. However, the focus of almost all of the previous studies was limited to climatic impacts on selected food crops. To date, no study has been conducted to measure the economic impacts of climate change on overall crop farming in Bangladesh. Some studies have already been conducted in the neighboring countries such as Sri Lanka, India and Pakistan to assess the economic impacts of climate change on agriculture (Seo *et al.*, 2005; Kumar, 2011; Mishra *et al.*, 2015; Arshad *et al.*, 2016). All the studies reported the significant impacts of climate change on agriculture, but a wide variability in loss and gain in different regions. This emphasizes the need for assessment of climate change impacts on crop farming and their spatial variability in Bangladesh.

The primary objective of this study is to assess the long-term impacts of climate change on net incomes from crop farming in Bangladesh. To achieve this, we used Ricardian regression models using a unique dataset of 420 farm households located across different climatic zones of the country. We also analyzed the marginal impacts of climate change and the potential future impacts of different climate scenarios on net crop incomes. Finally, based on the analytical findings, we suggest some policy measures that may enhance the adaptive capacity of the country's farming systems in response to climate change. The rest of the paper is structured as follows: Section 2 presents the materials, methods, and data, Section 3 discusses the results, and Section 4 conclusions.

2. Materials and methods

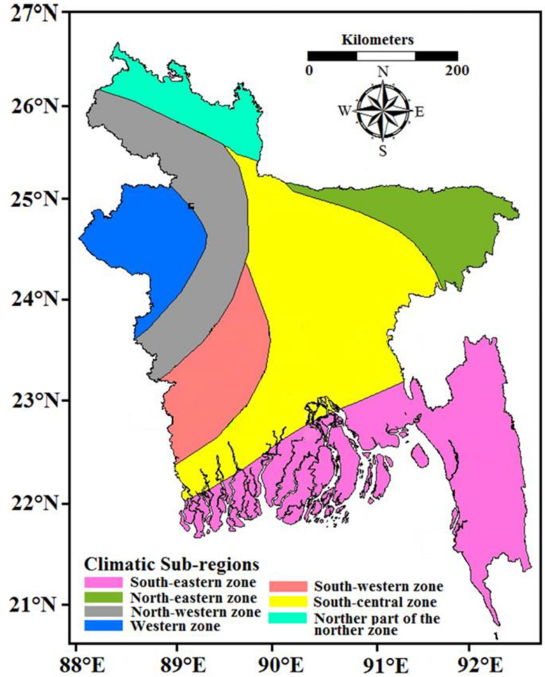
2.1 Location of the study

Bangladesh (latitude: $20^0$34'N-$26^0$38'N; longitude $88^0$01'E-$92^0$41'E) (Figure 1) has a tropical monsoon climate distinguished by heavy seasonal rainfall, high temperatures, and high humidity. The average annual rainfall fluctuates from 1,500 mm in the west-central to over 3000 mm in the southeast and northeastern parts of the country. More than 70 per cent of total rainfall in Bangladesh occurs during monsoon (July to September). The mean summer and winter temperature ranges from 30 to 40°C and 18 to 22°C respectively, whereas April is the hottest and January is the coldest month [Bangladesh Meteorological Department (BMD), 2016]. Based on climatic conditions, the land of Bangladesh has been divided into 7 climatic zones, as shown in Figure 1. There are two distinct cropping seasons: Rabi (mid-November to mid-March) and Kharif (mid-March to mid-November). The Kharif season is further sub-divided into two parts namely Kharif-I (mid-March to mid-July) and Kharif-II (mid-July to mid-November). Common Kharif crops include Aus and Aman rice, jute, and summer vegetables, while the Rabi crops include Boro rice, wheat, potato, pulses, oilseeds, and winter vegetables.

2.2 Data

2.2.1 Primary data. The primary data used in this study were collected using a disproportionate stratified random sampling technique to have a representative sample across all 7 climatic zones in Bangladesh (Arshad *et al.*, 2016). The climatic zones shown in Figure 1 were used as a basis for stratification. Each climatic zone was treated as one stratum. Three administrative districts were selected from each stratum randomly (Figure 2). From each selected district, two Upazilas (lower administrative units) were randomly selected whereas one village from each Upazila and ten farm households from each village were subsequently selected randomly. This resulted in 60 farm households from each climatic zone, totaling 420 respondents across all climatic zones. The selected districts represent a broad degree of agro-climatic, socio-economic and geographic features of Bangladesh.

The data were collected through field surveys conducted between January 2017 and April 2017 considering the cropping seasons of 2015-16. The survey questionnaire was designed to collect detailed information on the socio-economic characteristics of the sampled households including basic household information (gender, farmer's age, education, household size etc.), and the farm characteristics which include farming experience, farm area, soil types, access to bank credit, distance to market, access to extension services, and irrigation facilities. We also collected information on farmers' perceptions about climate



Source: Prime Minister's Office database, Bangladesh, http://lib.pmo. gov.bd/maps/images/bangladesh/Climate. gif

Figure 1.
The seven climatic zones of Bangladesh, adapted from "Seven climatic zones of Bangladesh"

change and changes in the local climatic patterns observed by farmers over the past decades. In addition, we collected information on current adaptation measures undertaken by the farmers in the study area (Table III). Net crop income per hectare is a core variable of Ricardian regression analysis. To estimate net crop income, farmers were asked in detail about their agriculture management practices, input and output costs. These include crop types, growing seasons of different crops, transportation and miscellaneous cost, cost and amount of inputs such as labor, irrigation, seeds, pesticide, fertilizer etc.

2.2.2 Secondary data. We collected 46 years (1971-2016) climate data on monthly average temperature and monthly average rainfall from the Bangladesh Meteorological Department, Dhaka. These climate data were interpolated from the respective meteorological stations located in the surveyed districts and climatic zones under the study. After testing a number of alternative definitions of seasons, dry (November-March) and wet (April-October) seasons were considered for the analysis. Due to the country's geographical location and small areal extent, average winter (21.16°C) and summer (28.11°C) temperatures of Bangladesh do not vary significantly. The dry (Rabi) and wet (Kharif) seasons are also the coldest and the hottest seasons respectively.

2.3 Ricardian methodology

The relationship between climate and agriculture is typically modeled using three approaches: crop growth simulation models, agro-economic models, and integrated

Source: Government of Bangladesh (2014)

Figure 2.
Map of Bangladesh zones using different colors showing surveyed districts

assessment models such as computable general equilibrium and whole farm models (Mishra *et al.*, 2015). The basis of these models is on climate-crop physiology and development. The first two modeling approaches can include some adaptation and crop management practices such as change of planting dates, variety selection, and fertilizer use. However, as both the modeling approaches are crop-specific, they are unable to account for other adaptation measures such as responses to economic stimuli including input replacement, price variations, crop shifting, and multi-cropping. Without accounting for such behavioral responses, those approaches can lead to an overestimation or underestimation of the climate impacts.

For the development of an unbiased estimate of climate impacts, there is a need for a whole farm approach that allows for adaptation responses. The model that is currently being widely used across different countries to measure the economic impacts of climate change in the agriculture sector is the "Ricardian model", named after the work of economist David Ricardo (1772-1823). Mendelsohn *et al.* (1994) was the pioneer to develop this cross-sectional model. The basis of the model is on the observation that land rents capture the long-term productivity of the farm. The Ricardian model assesses the performance of farms across landscapes, capturing impacts of spatial variations in climate attributes and other factors including input prices, soils, and socio-economic factors where the value of the lands reflects the present value of the future stream of net farm income.

The main advantage of this model is that it accounts for adaptation because farmers tend to adapt to the climate where they live to maximize the outputs and farm incomes. Other important advantages of the model are:

- it does not require data over time which is very difficult and costly to collect, rather it needs data across geographic space where climate attributes vary;
- it is a flexible model as it allows to consider all major enterprise activities; and
- it is very ease to implement.

However, the Ricardian model has some limitations. The first drawback is the possibility of omitted variable bias, which is present in all cross-sectional analysis. Another concern is the inefficiencies of the land and labor prices/markets that may distort prices. It does not account for CO_2 fertilization effects. Furthermore, the model cannot capture transition costs of an instantaneous adaptation to a new technology against climate. However, sudden adaptation to new technology is never experienced. Another controversial drawback is concerned with irrigation (Schlenker *et al.*, 2005). It is also not an issue in the study area as maximum farms rely on irrigation (Shahid, 2010).

2.4 Empirical model specification

Following Mendelsohn *et al.* (1994), we specified the Ricardian model as:

$$V = f(C, H, F) \tag{1}$$

Where V is the net crop income per hectare; C is a vector of climate variables (temperature and rainfall); H is a set of household attributes that includes age and education of the respondents, household size, and farming experience; and F is a set of farm variables, including farming area, access to extension services, distance to market, access to farm credit, soil types, and access to irrigation. We define net crop income as the total crop income (farm gate price multiplied by quantity sold) less the total cost of production that includes the cost of hired labor, fertilizer, pesticide, seeds, irrigation, and transport. Net crop income was calculated by the following equation:

$$V = \sum P_i Q_i (X, C, H, F) - \sum P_x X \tag{2}$$

Where P_i is the market price of crop i, Q_i is the output of crop i, X is a quantity of all inputs purchased for producing of crop i, P_x is a vector of input prices respectively. The standard Ricardian model relies on the quadratic formulation of climate:

$$V = \beta_0 + \beta_1 C + \beta_2 C^2 + \beta_3 H + \beta_4 F + u \tag{3}$$

Where C and C^2 capture the levels and quadratic terms for climate variables respectively, while u is an error term. The quadratic term is included to capture the nonlinear relationships. If a positive number for the quadratic term is obtained, the function assumes a U-shaped form, whereas if the value is negative, the function assumes a hill-shape form.

From equation (3), we estimated the marginal impacts of a change in temperature and rainfall on net crop income, which can be specified as follows:

$$\partial NR/\partial T = \beta_1 + 2\beta_2 T \quad \text{and} \quad \partial NR/\partial R = \beta_3 + 2\beta_4 R \tag{4}$$

3. Results and discussion

STATA (version 14.0) was used to analyze the data and run the Ricardian model. Summary statistics of the climate and other variables are presented in Tables I, II and III. The endogeneity problem was countered by using reduced form model rather than the structural model. As we can only minimize the multicollinearity at a certain level, we omitted age variable which was correlated with the farming experience. We also excluded distance to market variable from our analysis as it was found statistically insignificant. To minimize the heteroscedasticity, a robust estimation was applied for estimating standard errors. In case of outliers, we excluded 24 households assumed to be outliers as they reported very high or very low income and very large or very small farm size.

3.1 Climate variables and net crop income

The regression coefficients estimated from the two Ricardian models are presented in Table IV. In the first model, we estimate the seasonal temperature and rainfall (with quadratic terms) data on net crop income alone. In the second model, we include farm and

Variables	Mean	SD
Net crop income (US$/Ha)	410.34	249.95
Temperature wet season (in degree Celsius)	28.11	0.53
Temperature dry season (in degree Celsius)	21.16	0.98
Rainfall wet season (in Millimeter)	300.38	106.21
Rainfall dry season (in Millimeter)	20.88	8.79
Gender (gender of the farmer) (1 = male, 0 = female)	0.97	0.18
Farmers' age (years)	48.39	9.24
Farmers' education (years of schooling)	6.11	2.17
Farm household size (number of household members)	6.15	1.42
Farming experience (years of experience)	26.49	9.05
Access to bank credit (yes = 1, No = 0)	0.40	0.49
Access to agricultural extension services (yes = 1, No = 0)	0.80	0.40
Access to irrigation (yes = 1, No = 0)	0.64	0.48
Distance to market (Kilometers)	2.60	1.27
Sandy soil (dummy variable) (Sandy soil = 1, non-sandy soil = 0)	0.27	0.44
Clay soil (dummy variable) (Clay soil = 1, non-clay soil = 0)	0.10	0.29
Farm size (hectare)	1.79	0.46

Table I. Summary statistics for the variables used in the analysis (sample size n = 396) household characteristics variables to control for additional extraneous elements that may affect crop output and income.

The results from both the models are robust. The estimated models explain 3 to 16 per cent of the observed variations in net crop income hectare and most of the parameters in the models have expected signs. We observed that the constant values are very high even though they do not hold much statistical value. The reasons may be the low number of observations and few explanatory variables. Climate variables showed a nonlinear relationship with net crop incomes which is consistent with the findings of recent Ricardian studies available (Kabubo-Mariara and Karanja, 2007; Mishra *et al.*, 2015; Arshad *et al.*, 2016; Huong *et al.*, 2018). The wet and dry season temperatures showed an upward and downward trend respectively which is somewhat surprising. But given that these two temperatures (wet and dry) are part of the summer cropping season (Kharif) and winter cropping season (Rabi), respectively. The summer cropping season in Bangladesh is a combination of the significant part of the spring, summer and fall, while the winter cropping season is a combination of the winter and earlier part of spring. Higher temperature in the earlier part of wet season may be beneficial because it helps in primary growth and development of crops, while a warmer climate in the later stages can have harmful effects, e.g. slowing down of crop growth. This might be reason that the wet temperature indicated an inverted U-shaped trend.

On the contrary, the relatively low temperature in the early stages of dry season may be detrimental to crop growth, but as it gets warmer in the later stages, it becomes beneficial for ripening and maturity of crops. Thus, dry temperature indicated a U-shape trend. However, in case of rainfall, the trends for wet and dry seasons were found hill-shaped which indicates that early stage rainfall in both seasons is favorable for crop farming in

Table II. Variability in net crop incomes across 7 surveyed climatic zones

Name of climatic zones	Mean net crop income (US$/Ha)	SD
South-central	381.04	239.87
South-western	456.21	232.47
Western	473.16	296.86
North-western	420.46	319.95
Northern part of the north region	405.33	239.23
South-eastern	370.18	186.29
North-eastern	366.02	228.59
Average	410.34	

Table III. Current adaptation strategies practiced by the farmers apart from irrigation

Adaptation strategies	(%) of sample households
Use of new crop varieties	52
Adjusting sowing dates	48
Crop diversification	33
Change in cropping pattern and rotations	21
Integrated farming systems	16
Moved to non-farm activities	13
Find off-farm job	11
Other strategies	13

Note: Columns may sum to >100% where farmers reported more than one adaptation measure

Variables	Model 1 Coefficient	Model 1 Robust t-statistics	Model 2 Coefficient	Model 2 Robust t-statistics
Temperature wet season	−13367.93***	−2.84	−11318.51**	−2.28
Temperature wet season squared	241.07***	2.86	205.42**	2.31
Temperature dry season	2656.94***	2.93	3060.22***	3.60
Temperature dry season squared	−62.83***	−2.97	−72.31***	−3.63
Rainfall wet season	6.19***	3.43	7.04***	3.95
Rainfall wet season squared	−0.00***	−3.16	−0.00***	−3.58
Rainfall dry season	27.44*	1.91	26.17*	1.86
Rainfall dry season squared	−0.52	−1.56	−0.50	−1.56
Farmer's educational level			8.11	1.43
Farming experience			3.86**	2.59
Farm household size			10.74	1.21
Access to agricultural extension services			50.11*	1.91
Access to bank credit			19.71	0.79
Access to irrigation			46.40**	2.04
Farm size			56.80***	3.01
Clay soil			−50.55*	−1.69
Sandy soil			−18.04	−0.70
Constant	156,177.10**	2.57	121,768.80*	1.90
n	396		396	
F	3.21***		2.81***	
R^2	0.0358		0.1653	

Notes: ***$p < 0.01$; **$p < 0.05$; *$p < 0.1$

Table IV. Ricardian regression models explaining net crop incomes across seven climatic zones in Bangladesh

Bangladesh. Our findings are somewhat consistent with those of the South African crop farming analysis conducted by Benhin (2008).

Among the households' socio-demographic variables, the farming experience was positively associated with net crop income ($p < 0.05$) which suggests that experienced farmers are a better custodian of their land and may have good knowledge and information on the changes in local climatic conditions. For example, applying various soil conservation practices or using modern agricultural technologies, they are able to adapt to weather fluctuations and climatic variability (Huong *et al.*, 2017; Mishra and Pede, 2017). In line with this rationale, access to irrigation facilities was also significantly and positively correlated with net crop income ($p < 0.05$). Farmers widely use irrigation especially groundwater irrigation to hedge against drought and heat stress, which also plays an important role to increase the productivity and hence net crop incomes in Bangladesh (Shahid, 2010). However, groundwater level in many regions of Bangladesh is declining due to higher abstraction, which may cause an increase in salinity and irrigation cost and eventually may affect farmers' income in the long run (Krupnik *et al.*, 2017).

The positive and significant influence of farm size on net crop income ($p < 0.01$) indicates the economies of scale that large farms are associated with higher productivity compared to small ones. A similar result was found by Nyuor *et al.* (2016) in a study of northern Ghana. Access to agricultural extension services is also positively associated with net crop incomes ($p < 0.1$). This result implies that access to extension information and services increase farmers' knowledge on crop management practices and hence the capacity to adapt to the changes in climate to improve their outputs and incomes (Joshi *et al.*, 2017; Trinh *et al.*, 2017). The coefficient of soil types indicate that both sandy and clay soils are associated with lower net incomes. However, only clay soil was found statistically significant ($p < 0.1$).

3.2 Estimates of marginal impacts

The results of the marginal impacts of climate variables on net crop incomes per hectare are presented in Table V. A 1°C increase in temperature during the wet season would result in an income gain of about US$15.64 per hectare while in the dry season it would cause a decrease of net income by about US$0.22 per hectare. The higher temperature in summer cropping season would negatively affect the net incomes due to the strong seasonal effect of the fall season. Increasing temperature in the earlier part of the summer cropping season would be helpful for crop growth, but the temperature rise in later part would be destructive to crop farming unless farmers are conscious of this seasonal effect and adapt their farming activities accordingly. On the contrary, higher temperature in winter cropping season would have a positive effect on net incomes due to the strong seasonal influence of the spring season.

The marginal impacts of increasing rainfall will lead to an increase in net incomes in both the wet and dry seasons. The total impact of a 1°C increase in temperature and 1 mm/month increase in rainfall would cause an increase in income by US$19.66 per hectare across all climatic zones of the country. However, higher rainfall in the summer cropping season would have a minimal positive impact on net incomes. This result implies that early rainfall in the summer cropping season would be more helpful to crop growth than the excessive rainfall in the later stages. Thus, the timely arrival of the summer monsoon and its regularity are crucial for crop production in Bangladesh. On the other hand, rainfall in the winter cropping season is statistically significant ($p < 0.05$). The implication of increasing rainfall in the winter cropping season would also be helpful for crop growth, output and hence the enhancement of net incomes. The results indicate that seasonal variations are a vital factor for net income in both the cropping seasons. A similar observation has been reported by Benhin (2008) in the South African climate context. Table V also indicates that net crop income is more elastic to the changes in temperature (1.13 per cent) than the rainfall (0.42 per cent).

The results of the marginal impact of temperature are quite interesting. As a humid tropical warm region, one would anticipate that an increase in temperatures would lead to a

Variable	Full model
1°C increase in temperature on net crop income (US$/Ha)	
Temperature wet	15.64
Summer cropping season	−54.23
Temperature dry	−0.22
Winter cropping season	33.46
Annual temperature	15.42
Annual elasticity	1.13
1 mm/month increase in rainfall on net crop income (US$/Ha)	
Rainfall wet	0.30
Summer cropping season	0.34
Rainfall dry	3.94**
Winter cropping season	4.23**
Annual rainfall	4.24
Annual elasticity	0.42
Total climate	19.66

Notes: **$p < 0.05$; US$1 = 80.64 BDT considering average exchange rates during the survey

Table V. Marginal impacts of climate on net crop incomes (US$/Ha) decrease in net incomes. Our analyses however revealed that net crop income increases with rising temperatures. The reasons may be the ample rainfall in monsoon and availability of groundwater resources which permit a very high fraction of irrigated farmland in Bangladesh (Shahid, 2010). Extensive use of groundwater irrigation and improved technologies enable farmers in the region to endure much higher temperatures. Shahid (2010) in his study on Bangladesh interestingly reported that climate change will increase daily use of water for irrigation by an amount of 0.88 mm/day at the end of this century. With irrigation, higher temperatures have led to more cropping seasons per year which helped farmers to increase their net incomes. Thus, Bangladesh's agriculture appears to be adapting against warming and will be benefitted mildly even in a warmer world. This is consistent with the study of Mendelsohn (2008), he reported that wet eastern regions of India (geographical position of Bangladesh is within this region) will benefit gently from the global warming. Our findings are also consistent with those from Southeastern China which show similar trends and robustness (Wang *et al.*, 2009).

3.3 Marginal impacts of climate across all climatic zones

To examine the distribution of impacts across different climatic zones, the marginal impacts of climate for each zone are calculated from the coefficients of the Ricardian regression model (Van Passel *et al.*, 2016). The obtained results are presented in Table VI. Estimated marginal impacts of temperature showed that most of the climatic zones would experience a positive effect on net incomes though the coefficients for all climatic zones are not statistically significant. The results of the positive effect of temperature rise on net incomes may be due to the use of different adaptation techniques undertaken by the farmers in the study area as discussed above. A 1°C increase in temperature will lead to an increase in annual net incomes between \$11 (USD) to \$48 (USD). Alternatively, the relatively colder climate zones such as south-eastern and north-eastern Bangladesh would experience a negative mean annual impact of US\$9.51-16.31 per hectare respectively. Among the seven climatic zones, the western zone which is characterized by hot climate would gain the

Climate zones	Wet season	Dry season	Annual
1°C increase in temperature on net crop income (US\$/Ha)			
South-central	13.90	−2.68	11.22
South-western	40.38	−17.06	23.32
Western	39.08	9.24	48.32
North-western	11.30	12.64	23.94
Northern part of the north region	6.96	19.45	26.41
South-eastern	19.85	−29.36	−9.51
North-eastern	−23.85	7.54	−16.31
1 mm/month increase in rainfall on net crop income (US\$/Ha)			
South-central	0.33	3.89**	4.22
South-western	0.41	3.94**	4.35
Western	0.41	4.67*	5.08
North-western	0.35	5.01	5.36
Northern part of the north region	0.31	5.40	5.71
South-eastern	0.20*	3.21**	3.41
North-eastern	0.08	1.48	1.56

Notes: $^{**}p < 0.05$; $^{*}p < 0.1$

Table VI. Marginal impacts of climate across the all zones highest US$48.32, indicating that higher temperatures increase net crop income in the zone. The reasons may be that the farmers of this region have already adjusted their crop management practices to changing climatic conditions such as increased irrigation applications to offset the effects of heat stress. The marginal impact of increased rainfall in the dry season showed positive relations with net crop incomes across all zones and most of them are statistically significant in different levels ($p < 0.05$ and $p < 0.1$) in comparison to the results of the wet season rainfall.

These results establish that the marginal impacts are not uniformly distributed and that there would be losses and gains due to climate change across the different climatic zones. It is therefore essential for policy planners to reduce the losses and to take benefit of the gains by selecting and assessing the efficiency of existing adaptation mechanisms and finding ways to support them.

3.4 Climate projections and its impacts on net crop incomes

We then examined the impacts of future climate change on crop farming in Bangladesh. In this connection, future changes in rainfall and surface temperature for each district were first estimated using two Coupled Atmospheric Oceanic General Circulation Models (AOGCMs). These models are the Beijing Normal University Earth System Model: BNU-ESM (Ji *et al.*, 2014) and the Canadian Earth System Model: CanESM2 (Chylek *et al.*, 2011). The data were downloaded from the Coupled Model Intercomparison Project Phase 5 (CMIP5) website (http://pcmdi9.llnl.gov). Simulated daily surface rainfall and mean temperatures from each model were averaged to produce estimates of monthly mean climatological changes (absolute temperature changes and relative percentage rainfall changes) for the periods 2021-2060 and 2061-2100 (relative to the historical 1971-2005) under an assumed Representative Concentration Pathway RCP8.5 (van Vuuren *et al.*, 2011).

Future projections of annual temperature and rainfall over Bangladesh and its impacts on net crop incomes are presented in Table VII. The estimates showed that both models forecasted increasing temperatures for Bangladesh in the range of 1.81-2.04°C by 2021-2060 and even higher levels of 3.68-4.47°C by 2061-2100 periods. In case of rainfall, BNU-ESM projected decreasing rainfall levels (4.8 per cent) by 2021-2060 whereas increasing trend is observed (5.47 per cent) by 2061-2100 periods. However, CanESM2 projected increasing rainfall levels (3.39-19.97 per cent) during the both periods. By using parameters of the fitted net income model of Table IV, we estimated the impacts of these AOGCM scenarios on net incomes for these two time-periods. It is observed that the increment in the net income per hectare is more in the period of 2061-2100 than 2021-2060 under both scenarios.

Moreover, to compare the distribution of impacts across the different climatic zones, impact estimates for each climatic zone are estimated at the mean of a climate variable at that agro-climatic zone (Seo *et al.*, 2005). The findings are presented in Table VIII. The result indicated that different climatic zones would not be uniformly affected by the future climate

Table VII. Impacts of selected climate scenarios on net crop incomes (US $/Ha)

Climate projection models	Change in temperature °C	(%) Change in rainfall	Change in net incomes
BNU-ESM: 2021-2060	1.81	−4.80	24.77 (6.04)
CanESM2: 2021-2060	2.04	3.39	44.29 (10.79)
BNU-ESM: 2061-2100	3.68	5.47	60.82 (14.82)
CanESM2: 2061-2100	4.47	19.97	93.82 (22.86)

Note: Percentage changes in parenthesis change. This finding is in line with the results by Seo *et al.* (2005). The results also reveal that the gains from the future climate change for the welfare of Bangladeshi farmers would be increase over the years as they would continue to use irrigation as a cushion for adverse climate effects.

4. Conclusions

This paper is an endeavor to assess the economic impacts of climate change on crop farming in Bangladesh using a Ricardian regression model. The regression results indicate that farmers' current net incomes are sensitive to climate. Seasonal temperature has a more pronounced effect on net incomes than seasonal rainfall. Farm and household characteristics including the availability of extension services, farm size, access to irrigation and farming experience were positively associated with net incomes, while clay soils were found to hurt net incomes. Subsequent estimates of marginal impacts revealed that crop net income is more elastic to changes in temperature than rainfall but with significant seasonal and spatial variations in impacts. The impacts of climate change projected by two AOGCMs namely, BNU-ESM, CanESM2 reveal that net crop income in Bangladesh would increase in the range of US$25-84 per hectare. The distribution of net income impacts indicated that different climatic zones will not be equally affected by future changes in climate.

The results of our study may guide the government policy makers and rural development practitioners in designing the appropriate adaption strategies in the country. Adaptation policies should target different climatic zones based on the contraints and potentials of each zone in liew of recommending uniform interventions. To increase the resilience of crop farming sector of Bangladesh, immediate actions are required taking the current and anticipated climate change impacts into consideration. Based on the findings, our study suggests some essential climate adaptation policy recommendations which the government and policy makers may consider to address the challenges that farmers are likely to face as a result of climate change. Such recommendations include strengthening research capacity for the development of new cultivars and farming techniques with the changes in climate, enhancement of various enterprise diversification activities, making provision of crop insurance program and strengthening agricultural extension systems for disseminating up-to-date agricultural adaptation technologies to the farmers. Diversifying and generating off-farm employment opportunities in rural Bangladesh may also be crucial measures for the sustenance of rural masses. The present study was focused only on climate change impacts on net crop incomes. Future studies may consider analyzing the climate change impacts on other agricultural sectors, e.g. fisheries and livestock to assess the economic benefits or losses. We also suggest more research efforts in future for in-depth

Climatic zones	BNU-ESM 2021-2060	BNU-ESM 2061-2100	CanESM2 2021-2060	CanESM2 2061-2100
South central	20.55 (5.00)	56.60 (13.79)	38.78 (9.45)	89.60 (21.84)
South-western	23.44 (5.71)	68.83 (16.77)	52.29 (12.74)	101.82 (24.81)
Western	58.50 (14.26)	94.55 (23.04)	78.02 (19.01)	126.67 (30.87)
North-western	34.42 (8.39)	70.47 (17.17)	53.94 (13.15)	103.47 (25.22)
Northern part of north	37.24 (9.08)	73.28 (17.86)	56.75 (13.83)	106.28 (25.90)
South-eastern	−1.29 (-0.31)	34.76 (8.47)	18.23 (4.44)	67.76 (16.51)
North-eastern	−9.64 (-2.35)	26.40 (6.43)	9.86 (2.40)	59.40 (14.48)

Note: Percentage changes in parenthesis

Table VIII.
Forecasted average net crop incomes (US $/Ha) across different climatic zones

analyses of the economic impacts of climate change on farm income at the rural household level using a more holistic approach.

References

Agrawala, S.T.O., Ahmed, A.U., Smith, J. and Aalst, M.V. (2003), *Development and Climate Change in Bangladesh: Focus on Coastal Flooding and the Sunderbans*, Organisation for Economic Co-operation and Development (OECD), Paris.

Amin, R.M., Zhang, J. and Yang, M. (2015), "Effects of climate change on the yield and cropping area of major food crops: a case of Bangladesh", *Sustainability*, Vol. 7 No. 1, pp. 898-915, doi: 10.3390/su7010898.

Arshad, M., Amjath-Babu, T.S., Aravindakshan, S., Krupnik, T.J., Toussaint, V., Kächele, H. and Müller, K. (2018), "Climatic variability and thermal stress in Pakistan's rice and wheat systems: a stochastic frontier and quantile regression analysis of economic efficiency", *Ecological Indicators*, Vol. 89, pp. 496-506.

Arshad, M., Kachele, H., Krupnik, T.J., Amjath-Babu, T.S., Aravindakshan, S., Abbas, A., Mehmood, Y. and Müller, K. (2016), "Climate variability, farmland value, and farmers' perceptions of climate change: implications for adaptation in rural Pakistan", *International Journal of Sustainable Development and World Ecology*, Vol. 24 No. 6, pp. 532-544, doi: 10.1080/13504509.2016.1254689.

BBS (2015), "Statistical year book of Bangladesh", Bangladesh Bureau of Statistics, available at: bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/. . ./Yearbook-2015.pdf

Benhin, J.K.A. (2008), "South African crop farming and climate change: an economic assessment of impacts", *Global Environmental Change*, Vol. 18 No. 4, pp. 666-678, doi: 10.1016/j.gloenvcha.2008.06.003.

Bangladesh Meteorological Department (BMD) (2016), "AMIS project", Bangladesh Meteorological Department, Dhaka, available at: www.fao.org/. . ./160524_AMIS-CM_3.1.1_Availability_of_agro-meteorological_data

Calzadilla, A., Rehdanz, K., Betts, R., Falloon, P., Wiltshir, A. and Tol, R.S. (2013), "Climate change impacts on global agriculture", *Climatic Change*, Vol. 120 Nos 1/2, pp. 357-374, doi: 10.1007/s10584-013-0822-4.

Chowdhury, I.U.A. and Khan, M.A.E. (2015), "The impact of climate change on rice yield in Bangladesh: a time series analysis", *Russian Journal of Agricultural and Socio-Economic Sciences*, Vol. 40 No. 4, pp. 12-28.

Chylek, P., Li, J., Dubey, M.K., Wang, M. and Lesins, G. (2011), "Observed and model simulated 20th century Arctic temperature variability: Canadian earth system model CanESM2", *Atmospheric Chemistry and Physics Discussions*, No. 8, doi: 10.5194/acpd-11-22893-2011.

Ferdous, M.G. and Baten, M.A. (2011), "Climatic variables of 50 years and their trends over Rajshahi and Rangpur division", *Journal of Environmental Science and Natural Resources*, Vol. 4, pp. 147-150.

Government of Bangladesh (2014), "Seven climate zones of Bangladesh", Prime Minister's Office of the Bangladesh government, available at: http://lib.pmo.gov.bd/maps/images/bangladesh/Climate.gif

Huong, N.T.L., Bo, Y.S. and Fahad, S. (2017), "Farmers' perceptions, awareness and adaptation to climate change: evidence from northwest Vietnam", *International Journal of Climate Change Strategies and Management*, Vol. 9 No. 4, pp. 555-576, doi: 10.1108/IJCCSM-02-2017-0032.

Huong, N.T.L., Bo, Y.S. and Fahad, S. (2018), "Economic impact of climate change on agriculture using Ricardian approach: a case of northwest Vietnam", *Journal of the Saudi Society of Agricultural Sciences*, doi: 10.1016/j.jssas.2018.02.006.

IFRC (2010), "Bangladesh cyclone SIDR", *Final Report*, International Federation of Red Cross and Red Crescent Societies, Dhaka.

IPCC (2007), "Climate change: impacts, adaptation and vulnerability", *Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge.

IPCC (2014), "Climate change 2014", *Fifth Assessment Synthesis Report*, Intergovernmental Panel on Climate Change, Geneva.

Ji, D., Wang, L., Feng, J., Wu, Q., Cheng, H., Zhang, Q., Yang, J., Dong, W., Dai, Y., Gong, D., Zhang, R.H., Wang, X., Liu, J., Moore, J.C., Chen, D. and Zhou, M. (2014), "Description and basic evaluation of BNU-ESM version 1", *Geoscientific Model Development*, Vol. 7 No. 5, doi: 10.5194/gmd-7-2039-2014.

Joshi, B., Ji, W. and Joshi, N.B. (2017), "Farm households' perception on climate change and adaptation practices: a case from Mountain district of Nepal", *International Journal of Climate Change Strategies and Management*, Vol. 9 No. 4, pp. 433-445, doi: 10.1108/IJCCSM-07-2016-0099.

Kabubo-Mariara, J. and Karanja, F.K. (2007), "The economic impact of climate change on Kenyan crop agriculture: a Ricardian approach", *Glob Planet Change*, Vol. 57 Nos 3/4, pp. 319–330, doi: 10.1016/j.gloplacha.2007.01.002.

Krupnik, T.J., Schulthess, U., Ahmed, Z.U. and McDonald, A.J. (2017), "Sustainable crop intensification through surface water irrigation in Bangladesh? A geospatial assessment of landscape-scale production potential", *Land Use Pol*, Vol. 60, pp. 206-222, doi: 10.1016/j.landusepol.2016.10.001.

Kumar, K.S.K. (2011), "Climate sensitivity of Indian agriculture: do spatial effects matter?", *Cambridge Journal of Regions, Economy and Society*, Vol. 4 No. 2, pp. 221-235, doi: 10.109/cjres/rsr004.

Mendelsohn, R. (2008), "The impact of climate change on agriculture in developing countries", *J Nat Resour Pol Res*, Vol. 1 No. 1, pp. 5-19, doi: 10.1080/19390450802495882.

Mendelsohn, R. and Dinar, A. (2003), "Climate, water, and agriculture", *Land Econ*, Vol. 79 No. 3, pp. 328-341, doi: 10.3368/1e.79.3.328.

Mendelsohn, R., Nordhaus, W.D. and Shaw, D. (1994), "The impact of global warming on agriculture: a Ricardian analysis", *American Economic Review*, Vol. 84, pp. 753-771, available at: www.jstor.org/stable/2118029

Mishra, A.K. and Pede, V.O. (2017), "Perception of climate change and adaptation strategies in Vietnam: are there intra-household gender differences?", *International Journal of Climate Change Strategies and Management*, Vol. 9 No. 4, pp. 501-516, doi: 10.1108/IJCCSM-01-2017-0014.

Mishra, D., Sahu, N.C. and Sahoo, D. (2015), "Impact of climate change on agricultural production of Odisha (India): a ricardian analysis", *Reg Environ Change*, doi: 10.1007/s10113-015-0774-5.

Nelson, G.C., Valin, H., Sands, R.D., Havlík, P., Ahammad, H., Deryng, D., Elliott, J., Fujimori, S., Hasegawa, T., Heyhoe, E. and Kyle, P. (2014), "Climate change effects on agriculture: economic responses to biophysical shocks", *Proceedings of the National Academy of Sciences*, Vol. 111 No. 9, pp. 3274-3279, doi: 10.1073/pnas. 1222465110.

Nyuor, A.A., Donkor, E., Aidoo, R., Buah, S.S., Buah, J.B., Naab, J.B., Nutsugah, S.K., Bayla, J. and Zougmore, R. (2016), "Economic impacts of climate change on cereal production: Implications for sustainable agriculture in Northern Ghana", *Sustainability*, doi: 10.3390/su8080724.

Rosenzweig, C., Iglesias, A., Yang, X.B., Epstein, P.R. and Chivian, E. (2001), "Climate change and extreme weather events; implications for food production, plant diseases, and pests", *Global Change and Human Health*, Vol. 2 No. 2, pp. 90-104.

Ruamsuke, K., Dhakal, S. and Marpaung, C.O. (2015), "Energy and economic impacts of the global climate change policy on Southeast Asian countries: a general equilibrium analysis", *Energy*, Vol. 81, pp. 446-461, doi: 10.1080/23249676.2014.1001881.

Sarker, M.A.R., Alam, K. and Gow, J. (2012), "Exploring the relationship between climate change and rice yield in Bangladesh: an analysis of time series data", *Agric. Sys*, Vol. 112, pp. 11-16.

Schlenker, W., Hanemann, W.M. and Fisher, A.C. (2005), "Will US agriculture really benefit from global warming? Accounting for irrigation in the hedonic approach", *The Am Econ Rev*, Vol. 95 No. 1, pp. 395-406.

Seo, S.N., Mendelsohn, R. and Munasinghe, M. (2005), "Climate change and agriculture in Sri Lanka: a ricardian valuation", *Environment and Development Economics*, Vol. 10 No. 5, pp. 581-596, doi: 10.1017/S1355770X05002044.

Shahid, S. (2010), "Impact of climate change on irrigation water demand of dry season boro rice in northwest Bangladesh", *Climatic Change*, doi: 10.1007/s10584-010-9895-5.

Shahid, S. and Khairulmaini, O.S. (2009), "Spatial and temporal variability of rainfall in Bangladesh", *Asia-Pacific Journal of Atmospheric Sciences*, Vol. 45 No. 3, pp. 375-389.

Shahid, S., Harun, S.B. and Katimon, A. (2012), "Changes in diurnal temperature range in Bangladesh during the time period 1961-2008", *Atmospheric Research*, Vol. 118, pp. 260-270, doi: 10.1016/j.atmosres.2012.07.008.

Trinh, T.Q.T., Rañola, R.F., Camacho, L.D. and Simelton, E. (2017), "Determinants of farmers' adaptation to climate change in agricultural production in the central region of Vietnam", *Land Use Policy*, Vol. 70, pp. 224-231, doi: 10.1016/j.landusepol.2017.10.023.

Van Passel, S., Massetti, E. and Mendelsohn, R. (2016), "A ricardian analysis of the impact of climate change on European agriculture", *Environmental and Resource Economics*, Vol. 67 No. 4, pp. 725-760, doi: 10.1007/s10640-016-0001-y.

van Vuuren, D.P., Edmonds, J.A., Kainuma, M., Riahi, K., Thomson, A.M., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S. (2011), "The representative concentration pathways: an overview", *Climatic Change*, Vol. 109 Nos 1/2, pp. 5-31, doi: 10.1007/s10584-011-0148-z.

Wang, J., Mendelsohn, R., Dina, A., Huang, J., Rozelle, S. and Zhang, L. (2009), "The impact of climate change on china's agriculture", *Agricultural Economics*, Vol. 40 No. 3, pp. 323-337, doi: 10.1111/j.1574-0862.2009.00377.x.

Wheeler, T. and Von Braun, J. (2013), "Climate change impacts on global food security", *Science*, Vol. 341 No. 6145, pp. 508-513, doi: 10.1126/science.1239402.

World Bank (2010), *Climate Change Risks and Food Security in Bangladesh*, World Bank, Sher-e-Bangla Nagar, Agargaon, Dhaka, p. 1207.

Further reading

Ricardo, D. (1817), *On the Principles of Political Economy and Taxation*, John Murray, London.

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