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Farmers' Net Income Distribution and Regional Vulnerability to Climate Change: An Empirical Study of Bangladesh

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Abstract: Widespread poverty is the most serious threat and social problem that Bangladesh faces. Regional vulnerability to climate change threatens to escalate the magnitude of poverty. It is essential that poverty projections be estimated while bearing in mind the effects of climate change. The main purpose of this paper is to perform an agrarian sub-national regional analysis of climate change vulnerability in Bangladesh under various climate change scenarios and evaluate its potential impact on poverty. This study is relevant to socio-economic research on climate change vulnerability and agriculture risk management and has the potential to contribute new insights to the complex interactions between household income and climate change risks to agricultural communities in Bangladesh and South Asia. This study uses analysis of variance, cluster analysis, decomposition of variance and log-normal distribution to estimate the parameters of income variability that can be used to ascertain vulnerability levels and help us to understand the poverty levels that climate change could potentially generate. It is found that the levels and sources of income vary greatly among regions of Bangladesh. The variance decomposition of income showed that agricultural income in Mymensingh and Rangpur is the main cause of the total income difference among all sources of income. Moreover, a large variance in agricultural income among regions is induced by the gross income from rice production. Additionally, even in the long run the gradual, constant reduction of rice yield due to climate change in Bangladesh is not a severe problem for farmers. However, extreme events such as floods, flash floods, droughts, sea level rise and greenhouse gas emissions, based on Representative concentration pathways (RCPs), could increase the poverty rates in Mymensingh, Rajshahi, Barisal and Khulna—regions that would be greatly affected by unexpected yield losses due to extreme climatic events. Therefore, research into and development of adaptation measures to climate change in regions where farmers are largely dependent on agricultural income are important.

Keywords: income distribution; cost distribution; vulnerable region; adaptation measures; Bangladesh

1. Introduction

Bangladesh has experienced severe famines [1–3]. However, heavy investments in agriculture following these famines have given rise to enhanced food production and have caused significant increases in domestic rice production [4,5]. Both the cultivation techniques and cropping patterns relating to rice production have gradually changed in terms of yield potential [6,7]. Despite huge population pressures, the country has reached self-sufficiency in rice production [8–10]. Additionally, Bangladesh's economic situation is improving; as such, it is one among a rather small group of countries that have seen remarkable progress in terms of both economic performance and development indicators [11]. However, poverty remains a critical social concern in this country [6,12,13].

Climate change will have a largely adverse impact on agricultural production in Asia [14]. For particular geographical locations and due to other environmental reasons, Bangladesh is one of the world's most disaster-prone countries [15–18]. Given climate change impacts, natural resource constraints and competing demands, agriculture and food systems continue to face considerable challenges. The livelihoods of the poor who are directly reliant on agriculture already face a profound threat due to the current climate change in Bangladesh [19,20], which could lead to increased pauperization. At the household level, climate change significantly affects food production [21] which in turn influences food prices and directly affects the poverty of low-income household [22,23]. Agricultural income and non-farm income are the most significant factors in poverty reduction among rural people [24–27]. However, Chaudhry and Wimer reported that household income plays a vital role in the social and economic development of a community and income from agriculture might result in increasing per capita income [28].

Agriculture is strongly influenced by weather and climate, which in turn have impacts on agricultural production [29]. Over the last three decades, temperature has been increasing in Bangladesh [30,31] and the average daily temperature is predicted to undergo an increase of 1.0 °C by 2030 and 1.4 °C by 2050 [32,33]. The annual rainfall is also unevenly distributed in some areas of Bangladesh. Rainfall patterns might change with increasing temperature and drought occur in some areas; however, total rainfall sometimes increases and heavy rainfall induces floods in Bangladesh. Increasing temperature also enhances extreme events, such as cyclones in coastal areas and adversely affects rice production [7,30,34–36]. Additionally, climate change is projected to affect agriculture and it is very likely that climate change will induce significant yield reduction in the future due to climate variability in Bangladesh [37–39], with a projected decline of 8–17% in rice production by 2050 [33,40]. In Bangladesh, nearly 80% of the total cropped area is dedicated to rice production, accounting for almost 90% of total grain production [39,41–46]. Agricultural production, farm income and food security are significantly affected by seasonal growing temperatures [47].

Some previous studies have projected the impacts of climate change on food production and national food security [48,49], as well as their impact on agricultural production, by collecting information under drought, rainfall, sea level rise, flood and temperature increases [39,43,50] and the impact of coastal flooding on rice [7,51,52]. However, there have been fewer studies from micro or regional points of view based on integrated household survey data or poverty measurements under yield reductions of crops due to climate change vulnerabilities. Farmers' low incomes are the main reinforcing factors in poverty traps, so this context of research is not sufficient. To consider suitable adaptation technologies and policies for farmers, impact projections in terms of regional characteristics and poverty are needed far more. To alleviate the severity of climate change's impact on farm production and poverty, adaptation strategies, such as new crop varieties, changing planting times, homestead gardening, planting trees and migration, are vital approaches [6]. Furthermore, research that projects climate change's impacts on poverty or that pinpoints especially vulnerable regions and the vulnerability of farm household income under the impact of climate change is still needed [53,54]. Using statistical analysis, the current study attempts to derive an understanding of regional characteristics in terms of income and agriculture and to assess the contributions of different components on the observed total variance of income and cost, with an eye towards determining regional vulnerability to climate change and projecting the potential effects of climate change on poverty in Bangladesh. In this study, we used high-quality plot-level agricultural production data from the nationally representative survey by the International Food Policy Research Institute (IFPRI) (Appendix A.1). We used different analytical techniques to evaluate regional characteristics and to assess the potential climate change impacts on farm production and poverty under newly developed representative concentration pathways (RCPs) and other climate scenarios. The objective of this study was to project the poverty under the impacts of climate change on crop production and to provide possible adaptive measures.

The paper is designed as follows: we draw a review of the related literature concerning climate change, vulnerability and poverty in Section 2; Section 3 is the methodology section, in which we describe the data sources, compilation procedures and the analytical approaches of the data; in Section 4, descriptive statistics and empirical results of the analysis with discussion are presented; and in Section 5, we conclude by emphasizing the future research directions and some policy guidelines.

2. Review of the Literature

The research on climate change scenarios and poverty in terms of regional characteristics is outlined concisely in this section. Climate change is a reality that is occurring and will increasingly affect the poor; moreover, it is a serious threat to poverty eradication [55]. Poor agricultural communities are always disrupted by climate change's impact on household food security and poverty [56,57]; climate change impacts could increase household poverty [55]. Poverty as a dynamic and multidimensional condition is characterized by the interaction of individual and community features, socioeconomic and political issues, environmental processes and historical circumstances. Particularly in less developed countries and regions through several direct and indirect channels, climatic variability and change can worsen poverty [58]. Lade et al. reviewed the socio-ecological relationship in rural development concepts, emphasizing the economic, biophysical and cultural aspects of poverty. This study classified the poverty alleviation strategies and developed multidimensional poverty trap models and it stated that interventions that ignore nature and culture can reinforce poverty [59].

A multi-factor impact analysis framework was developed by Yu et al. [39] and using this framework [50] Ruane et al. provided sub-regional vulnerability analyses and quantified key uncertainties in climate and crop production. Climate change impacts increase under the higher emissions scenarios and agriculture in Bangladesh is severely affected by sea level rise [50]. Over the same period, several attempts have been made regarding climate scenario development in Bangladesh, mainly using Global Climate Models (GCMs) and in some cases Regional Climate Models (RCMs) [60–62]. From these studies, the overall conclusions include increases in temperature and rainfall, different drought seasons and impacts on crop production.

The projected future yield of rice cultivars in 2030 and 2050 in different areas of Bangladesh by DSSAT crop modelling showed that Bagerhat, Dinajpur, Gaibandha, Maulvibazar, Panchagarh, Rangpur, Sirajganj and Thakurgaon districts will have high yield losses due to climate change impacts. Rainfall, temperature and CO_2 affect the yield for *aman* rice in Rangpur and Khulna divisions and for *boro* rice in Rajshahi, Barisal and the southwest region [63]. Changing patterns of rainfall and temperature in different regions of Bangladesh are significantly higher, compared to IPCC predictions. For sustainable adaptation, location-specific management of seed, crop and irrigation is needed [21]. Soil tolerance, flood tolerance and shorter varieties of rice and other crops could be used to adapt to climate change impacts [64]. Climate change is likely to have an adverse effect on rice and wheat production [5] and significant yield reductions in the future due to climate variability [38] are also directly associated with extreme weather events [19]; due to population pressures, future food production is a challenge in maintaining food security in Bangladesh [5]. Food demand changes because of urbanization, population structure, among other factors; however, food supply can change due to extreme climate change impacts on agricultural production in Bangladesh. The combined effects on rice of major climatic variables were checked by Karim et al. and they found that rice yield would decrease by 33% in both 2046–2065 and 2081–2100 for Rangpur, Barisal and the Faridpur region [65].

Total annual income of a farm household depends on farm and non-farm income. Farm income is always unstable due to the dependency of weather and even if farm income is high poverty may occur;

however, higher non-farm income could reduce the poverty [28]. Farm households in Bangladesh are the most prone to the impacts of climatic hazards. Uncertainty is high in farm income and it depends on the wide fluctuations of yields and prices. Unexpected weather can easily damage crop production, rendering farms more vulnerable [66]. In Bangladesh, farmers are fully dependent on weather for their crop production, resulting in lower farm income if extreme climatic events occur. Unexpected yield reductions cause fluctuating farm income and increase food insecurity and poverty. Agriculture is the main source of income of farmers in Bangladesh [8,21] and it might cause per capita income to increase, which in turn could further reduce poverty. The participation of government programs and off-farm income is significantly important in reducing poverty [24].

There has been much research on climate change impacts, adaptations and projections in agriculture. The IPCC's fifth assessment report showed that food production in Asia will vary and decline in many regions under the impact of climate change [37]. Rajendra et al. focused on climate change impacts on farming in northern Thailand, where the vulnerability of farm households persists under the negative impact of climate change [54]. Yamei et al. assessed the adverse effects of future climate on rice yields and provided potential adaptive measures [67]. Nazarenko et al. examined the climate response under a representative concentration pathway (RCP) for the 21st century [68], while there are fewer comprehensive scenarios for the whole country regarding farm income and poverty projections.

In addition, in-depth empirical research on farm income distribution and regional vulnerability to climate change has been lacking. Furthermore, most of the previous studies of climate change impacts on agricultural production have been for specific regions. However, a comprehensive study of climate change impacts comparing the regions of Bangladesh could be enormously significant. One of the motivations of the study is to summarize the farmers' net income scenarios for all of the regions of Bangladesh, assessing the contributions of different components on the observed total variance in income and costs and possible poverty under climate change impacts on agricultural production. Moreover, understanding farmers' local economic situations and coping strategies with climate change impacts could have immense significance for regional point of view. Based on actual farm income, this study evaluates the projected farm income under the scenario that extreme climatic events occur. It then determines the projected poverty to identify vulnerable regions and to suggest appropriate coping and poverty alleviation strategies.

3. Methodology

3.1. Survey Data

In its empirical analysis, this study uses cross-sectional data drawn from nine administrative regions across Bangladesh. These data were derived from the International Food Policy Research Institute (IFPRI), which adopted a multi-stage stratified random sampling method to collect primary data: first a selection of primary sampling units (325 villages) and then a selection of farm households (20 farms) from each primary sampling unit. Randomly selected villages with probability proportional to size (PPS) sampling using the number of households from the Bangladesh population census data in 2001. Randomly selected 20 farm households in each village from the aforementioned national census list. IFPRI researchers designed the Bangladesh Integrated Household Survey (BIHS) (Appendix A.1), the most comprehensive, nationally representative household survey conducted to date. Plot-wise crop production data were collected via semi-structured questionnaire by the IFPRI from 6503 sample farmers across Bangladesh vis-à-vis cultivated crops; the survey period was from 1 December 2010, to 30 November 2011. The original data were collected in a typical agricultural year according to rice production statistics; there was no severe crop loss in the 2010 or 2011 rice years in Bangladesh [69].

3.2. Data Compilation

This study models the poverty rate change under climate change vulnerability in different regions of Bangladesh. Based on the purpose of this study, to analyze the data we applied descriptive, inferential, statistical and multivariate techniques. Plot-wise raw data were compiled in line with the study objectives. We compiled data pertaining to many income sources for each separate household into some important sectors. In addition, for agricultural activities, we also compiled all types of input cost data into some important cost items and output values for each crop. We then compiled and combined them into one data set of households for all 6503 farms. Bangladesh consists of 30 agro-ecological zones (AEZs) that overlap with each other [69,70]. For the convenience of this research, some homogenous agro-ecological zones were combined into the nine administrative regions with their geographical locations. In this manner, we tried to develop nine mutually exclusive regions for our research. To overcome the resulting challenge in consistency under the same impact of climate change in each region [50], we categorized all the sample farmers per the nine administrative zones of Bangladesh, calling each a division (nine different colors indicating the individual divisions) (Figure 1): Barisal (700 sample farmers), Chittagong (300), Comilla (660), Dhaka (1380), Khulna (1020), Mymensingh (600), Rajshahi (580), Rangpur (543) and Sylhet (720).

Figure 1. Map of the objective regions of Bangladesh.

We estimated the costs and incomes associated with 17 major crops produced by farmers in Bangladesh (each is considered an important crop); other crops (such as pulses, oil seeds, spices except for chili and onion, vegetables, leafy vegetables, etc.) and all types of fruits (such as banana, mango, pineapple, jackfruit, papaya, guava, litchi, orange, etc.) were added to another group, "all other crops." The 18 groups are *aus* (Appendix **??**), rice local, *aus* rice LIV, *aus* rice HYV, *aman* rice local, *aman* rice LIV, *aman* rice HYV, *aman* rice Hybrid, T *aus* rice HYV, *boro* rice HYV, *boro* rice Hybrid, wheat local, wheat HYV, maize, jute, potato, chili, onion and all other crops.

To estimate per-capita income for farm household members in all nine administrative regions of Bangladesh, this study considers all income sources, including income from agriculture. The basic unit of analysis is each farm, while farming is the only significant source of income among other sources, such as employment, small business and so on, for the family in a one-year period. Net income for the farm household from agriculture was calculated by deducting total input costs from gross income:

$$\pi = \sum_i P_i Y_i - \sum_i \sum_j P_{ij} X_{ij} \quad (1)$$

where π is net income, P_i is price of crop i, Y_i is production of crop i, P_{ij} is price of input j for crop i and X_{ij} is input j for crop i.

This analysis used only the accounting costs to estimate net income from agriculture (Appendix B.1); these costs include the so-called explicit costs actually incurred by the farms and in surveys, farmers reported their own cost data. For this reason, this study regards supply of one's own land and family labor as part of agricultural income. The farm gate price of each crop for each household was used to estimate gross income derived from agricultural crops, livestock and poultry and fish production; additionally, actual input prices were used to estimate the production costs cited by each farmer and in-kind payments by crops are deducted for estimating gross income. For farmers with no information about farm gate prices or input prices for their respective crops, we used the average prices from the region. This study crosschecked the farm gate prices and input prices with data pertaining to the average national retail price data of select commodities in Bangladesh [71] during the aforementioned study period. Farmers used farm gate prices to sell their crops and for this reason, there was some divergence between national retail prices and the farmers' prices. To estimate per-capita income for each member of the farm, this study assumes that all negative returns tend towards zero so that we can calculate shares of income sources.

Income data were collected for each household and these data were used to calculate overall household income. Income was broadly classified into seven major sectors, as follows:

(i) Agricultural crop income: income from all crop types produced by farmers throughout the year;
(ii) Income from fish/shrimp farming;
(iii) Income from livestock and poultry enterprises;
(iv) Nonagricultural enterprise income: income from nurseries, food processing, fishing, nonagricultural day labor, retail, wholesale, construction, manufacturing, wooden furniture and other businesses;
(v) Remittances: remittances from within or outside Bangladesh, with the persons who sent the remittances excluded from their respective households;
(vi) Employment: both formal and informal employment, income from self-employed and/or owned businesses that are not agricultural, income received from relatives and friends not presently living with the household and so on; and
(vii) Other income: income received from land rent or property rent, income from life and nonlife insurance, profit from shares, gratuities, or retirement benefits, income from lotteries or prizes, interest received from banks, charity assistance, other cash receipts and/or other in-kind receipts.

These seven sectors of household income were used to determine the actual income and income sector shares, both of which reflect income distributions significantly.

3.3. Analytical Approach

This study used four types of statistical analysis.

3.3.1. Analysis of Variance (ANOVA)

After dividing farm households into the nine aforementioned regions, we conducted single-factor analysis of variance (ANOVA) to examine differences among the farm households of the nine regions in Bangladesh in terms of mean per-capita income.

3.3.2. Cluster Analysis

The cluster analysis (CA) technique was used to determine the main and dominant income sources in Bangladesh's various regions. Environmental (i.e., topographical) divergence is a common phenomenon in Bangladesh and it diversifies farm production, although farm households within a certain region do tend to be similar. Ward's hierarchical method and the partitioning method can be used to determine the most appropriate clusters regarding the main income sources in each region. A dendrogram—a graphical representation of the hierarchy of nested cluster explanations—is a manifestation of Ward's method and it provides clues for finding the preferable number of clusters regarding income sources.

3.3.3. Decomposition of Variances

To understand the interregional differences and to assess the contributions of different components to the observed total variance of input cost and income, different crop production data are used [72–75]. These data include per hectare crop yields, prices and all costs at the farm level and we decompose the variances in net cost and net income into different factors using the following relations.

$$\mathrm{V}(X \pm Y) \;=\; \mathrm{V}(X) + \mathrm{V}(Y) \pm 2\mathrm{Cov}(X, Y) \tag{2}$$

where X and Y are stochastic variables, such as the costs of inputs or incomes from different sectors; V $(\cdot)$ is variance and Cov $(\cdot)$ is covariance.

3.3.4. Projections: Log-Normal Distributions

There are different types of probability distributions studied in probability theory. Lognormal distribution is one of the most important one and was established long ago [76–78]. Lognormal distribution is a type of a continuous distribution. It is a probability distribution in which the logarithm of the random variable is distributed normally. This distribution is closely related to the normal distribution. Lognormal distribution is very commonly used in the social sciences, economics and finance [79].

Arata [80] pointed out that the income distribution among individuals is very important and is one of the main themes in economics. Income distribution is widely understood to be well described by a log-normal distribution.

Lognormal distribution has two parameters: mean (μ) and standard deviation (σ). If x is distributed log-normally with parameters μ and σ, then log(x) is distributed normally with mean μ and standard deviation σ. The log-normal distribution is applicable when the quantity of interest must be positive since log(x) exists only when x is positive. A positive random variable X is log-normally distributed if the logarithm of X is normally distributed.

$$ln(X) \;\sim\; N\left(\mu,\, \sigma^2\right) \tag{3}$$

Let Φ and φ be, respectively, the cumulative probability distribution function and the probability density function of the N (0, 1) distribution.

The probability density function of the log-normal distribution is;

$$f(x|\mu,\sigma) \;=\; \frac{1}{x\sigma\sqrt{2\pi}} exp\left\{\frac{-(lnx-\mu)^2}{2\sigma^2}\right\};\; x > 0 \tag{4}$$

If we substitute a poverty line into x and integrate the probability density function up to x, we can obtain a poverty rate. The poverty line, which is estimated by world Bank, is inserted into the equation [12,67].

We estimate the incomes of all sample families on the assumption of climate change impacts and draw the distribution of the estimated incomes, assuming that the distribution follows log normal distribution. To draw log normal distribution, we must find the mean and standard deviation of $ln(x)$ (Appendix B.2). From the actual per-capita income of household members in the study areas, we obtain the actual distribution of per-capita income using the lognormal distribution. Next, we project the crop yield loss from the assumption of the literature reviews and we estimate the projected per-capita income. From projected per-capita income using lognormal distribution, we obtain the estimated distribution of per-capita income. By simulating these two distributions, we find the poverty rate graph.

4. Results and Discussion

4.1. Comparison of Income Levels Among Regions

Agricultural income is a key driver in reducing poverty in Bangladesh, where it accounted for 90% of all poverty alleviation between 2005 and 2010 [81]. In terms of employment, Bangladesh's economy is primarily dependent on agriculture. Approximately 85% of the population is directly or indirectly attached to the agriculture sector [38,69].

Agriculture continues to be the main source of income in the sample households in all regions (Table 1) and this result is consistent with Hossain and Silva (2013) [5]. However, in all regions, nonagricultural profit and employment are important income sources and these results are consistent with Bangladesh Economic Review [45]. The amount of remittances varies by region: that in Sylhet is not the highest nationally but the people there do consider remittances to be the main income source in the region. The agricultural income is higher in Rajshahi than in other regions and the per capita income of this region per the study sample is US$ 423.6 (Table 2). Diversification of agricultural crops results in this region having highest income from agriculture.

Table 1. Each income sector's share in total household income (%), by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
Agril. crops	12.71	8.14	5.50	13.55	19.43	20.15	18.72	21.41	9.03	14.32
Main crops	6.08	2.89	2.34	8.25	10.81	11.44	11.72	14.84	6.15	8.36
Other crops	6.63	5.25	3.16	5.30	8.62	8.71	7.00	6.58	2.87	5.96
Fish	9.23	1.54	0.57	2.18	7.93	6.06	2.87	1.14	3.16	3.96
Livestock	2.19	1.17	1.48	3.60	6.15	5.12	4.43	3.10	1.80	3.47
Non-ag. profit	20.76	19.25	14.13	21.22	18.09	17.66	19.61	14.88	20.05	18.80
Remittance	11.04	24.99	41.48	15.68	7.64	9.11	4.48	7.58	17.77	15.22
Employment	38.91	44.35	30.80	41.10	38.52	39.04	38.83	50.54	44.02	40.10
Other income	5.16	0.55	6.04	2.66	2.23	2.86	11.06	1.35	4.18	4.12
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet, BD = Bangladesh, Main crops = *Aus*, *Aman* and *Boro* rice and other crops = Wheat, maize, jute, potato, chili, onion and so on.

Table 2. Mean, median and standard deviation of per-capita income (US$/yr), by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
Mean	308.93	336.75	378.35	362.17	369.84	307.63	423.63	308.76	301.63	327.55
Median	289.93	217.83	246.25	242.87	254.11	215.04	283.14	226.99	204.82	232.94
SD	314.75	418.11	314.22	403.66	382.81	278.08	372.71	246.61	301.02	348.64
PR	0.51	0.48	0.46	0.46	0.42	0.51	0.33	0.47	0.49	0.46

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet, SD = Standard deviation and PR = Poverty rate.

Table 1 shows significant differences in main income sources among farmers in various regions in Bangladesh. Employment is the predominant income source in most regions, followed by nonagricultural profits and agriculture. The share of agriculture in total income varies by region. Among Bangladeshi farming households, the employment share is 40.10%, although the overall share of agriculture in total income is 14.32%. Rangpur has the highest share of agricultural income in total annual income (21.41%), followed by the Mymensingh region (20.15%). Comilla's share of remittances in total annual income was highest (41.48% of total income); in comparison, the share generated by agricultural crops in Comilla was only 5.50%. Currently, overseas workers are more often from the Comilla region than other regions in Bangladesh, with a significant proportion of them sending remittances, becoming a vital source of income in the Comilla region. Rice and other crops were the main sources of income among the sampled farm households in the study areas (Appendix C). Incomes from maize and potato appear to be growing but their respective shares remain small. There are regional land conditions and climate differences among Bangladesh's regions, so wheat, maize, onion and potato production is not familiar to all farmers. Consequently, farmers in all areas of Bangladesh tend to focus on rice cultivation.

Table 2 shows descriptive statistics of income status by region. Poverty rates were estimated by applying the poverty line and the purchasing power parity from the World Bank [22] to log-normal income distributions. The findings presented in Table 2 indicate differences in mean, median and standard deviation of net incomes among the nine regions in Bangladesh; using these findings, one can pinpoint relatively rich and poor regions.

In terms of mean net income, incomes of sampled farm households in Rajshahi are the highest, while those of Barisal, Mymensingh, Rangpur and Sylhet are lower. As some farmers had negative or zero per-capita income, the standard deviation is relatively large in certain regions. The highest standard deviation value is found in Chittagong (US$ 418.1), reflecting a large income gap among the farmers there.

The highest poverty rate (i.e., 0.51) was found in Mymensingh and Barisal (Table 2), while the lowest (i.e., 0.33) was in Rajshahi; overall, the country's upper poverty rate is 0.46. The rates in Chittagong and Sylhet were also relatively low (i.e., 0.49). The officially estimated upper poverty rate and national average poverty rate are both in the vicinity of 0.35 [12,82], which makes sense because the original data were collected from rural, farming-engaged people and excluded affluent or single urban people.

Among regions where the poverty rates were high, Barisal, Mymensingh and Sylhet had the lower mean incomes. In contrast, Chittagong had the highest standard deviation, compared to the other regions. In the regions of Barisal, Mymensingh and Sylhet, it appeared that the mean income level was low; however, in the other regions, the mean income was large. These results show that these low-income regions are vulnerable regions and should be the targets of farmers' support policies.

From results of Table 2, this study found that there are differences in mean, median and standard deviation of net incomes among the nine regions in Bangladesh and for validation of this difference, we perform ANOVA and report the results in Table 3. Analysis of variance (ANOVA) is a statistical test designed to examine means across more than two groups by comparing variances, based upon the variability in each sample and in the combined samples. We analyzed the variance within and between the sample farmers to determine the significance of any differences in per capita income of farm household members among the regions of Bangladesh. The results of the overall F test in the ANOVA summary shows the results regarding the variability of means between groups and within groups. As indicated, the overall F test is significant (i.e., p-value < 0.05), indicating that means between groups are not equal and it is statistically concluded that there have been significant differences among the regions in terms of mean per-capita income.

Table 3. ANOVA mean differences across regions.

Source of Variation	SS	df	MS	F	p-Value	F Crit
Between groups	6.31×10^{10}	9	7.01×10^{9}	4.757462	2.39×10^{-6}	1.880604
Within groups	1.91×10^{13}	12,996	1.47×10^{9}			
Total	1.92×10^{13}	13,005				

The first column in ANOVA provides us with the sum of squares between and within the groups and for the total sample farmers. The total sum of squares represents the complete variance on the dependent variable for the total sample. The second column represents the degrees of freedom, ($n - 1$). The total degrees of freedom represent 13,006 − 1 = 13,005; degrees of freedom between groups equals the number of groups minus one (10 − 1 = 9). The within groups degrees of freedom equals 13,005 − 9 = 12,996. The third (mean square) column contains the estimates of variability between and within the groups. The mean square estimate is equal to the sum of the squares divided by the degrees of freedom. The between groups mean square is 7.01×10^9; the within-groups mean square is 1.47×10^9. The fourth column, the F ratio, is calculated by dividing the mean square between groups by the mean square within the groups. The F ratio should be one if the null hypothesis is true, while both mean square estimates are equal. However, as shown in Table 3, larger F values (4.757462) imply that the means of the per capita income groups are greatly different from each other, compared to the variation in the individual sample farmers in each group. The next column is the significance level (p-value) and it indicates that the value of F ratio is sufficiently large to reject the null hypothesis. The significance level is 2.39×10^{-6}, which is less than 0.05. Therefore, the mean per capita incomes of sample households among the regions of the country were significantly different in the study year.

4.2. Regional Characteristics on Income Source

This section intends to classify regions of Bangladesh to determine the regional characteristics of income sources in each administrative region. Sectoral income shares from Table 1 are analyzed by cluster analysis and are shown in Figure 2. Here, a dendrogram depicts the income source relationships among the regions. The horizontal axis of the dendrogram (in Figure 2) represents the distance or dissimilarity between clusters and the vertical axis represents the objects (regions) of clusters. From the cluster analysis, this study attempted to find the similarity and clustering with the dendrogram, which visually displays a certain cluster shape. Regions that are close to each other (have small dissimilarities) are linked near the right side of the plot. In Figure 2, we note that Khulna and Mymensingh are very similar compared to the regions that link up near the left side, which are very different. For example, Comilla appears to be quite different from any of the other regions. The number of clusters formed at a particular cluster cutoff value can be quickly determined from this plot by drawing a vertical line at this value and counting the number of lines that the vertical line intersects. In this study, we can see that, if we draw a vertical line at the value of 18.0, four clusters will result. One cluster contains four regions, one contains three regions and two clusters each contain only one region, as shown in Figure 2, in which Barisal, Mymensingh, Khulna and Rajshahi are more alike than resembling Rangpur. In addition, Chittagong, Dhaka and Sylhet are more alike than resembling Comilla.

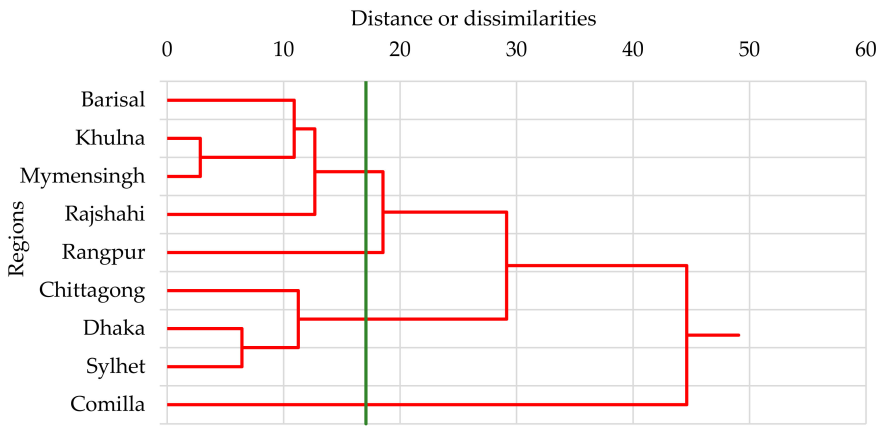

Figure 2. Dendrogram showing clusters for main income sources, by region.

Table 4 summarizes regional characteristics of income sources. Clusters 1 and 2 are largely dependent on agriculture. Clusters 3 and 4 are not largely dependent on agriculture. This result indicates the importance of agricultural research for clusters 1 and 2.

Table 4. Cluster characteristics of main income sources, by region.

Cluster	Region	Main Income Source	Distinction
1	Barisal, Mymensingh, Khulna, Rajshahi	Agricultural. crops, non-agricultural profit, employment	
2	Rangpur		Dominant Employment
3	Chittagong, Dhaka, Sylhet	Non-agricultural profit, remittance, employment	
4	Comilla		Dominant Remittance

Using the dendrogram in Figure 3 (agricultural crop share in total agricultural income analyzed by cluster analysis), four clusters were determined (Table 5) as the clusters suitable for representing agricultural crop income sources among the regions. We followed the same procedure for this dendrogram (Figure 3) that we followed in Figure 2.

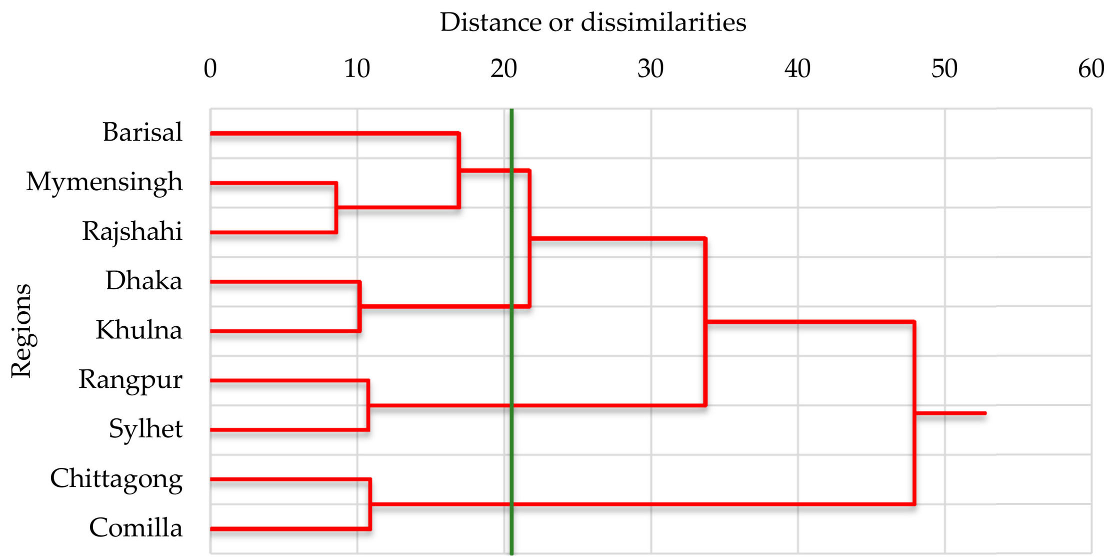

Figure 3. Dendrogram showing clusters for agricultural income sources, by region.

Table 5. Cluster characteristics of agricultural income sources, by region.

Cluster	Region	Main Income Source	Distinction
1	Barisal, Mymensingh, Rajshahi	Rice, other crops	
2	Rangpur, Sylhet		Dominant rice
3	Chittagong, Comilla		Dominant other crops
4	Dhaka, Khulna	Rice, jute, chili, onion, other crops	

The selected clusters show significant differences among the regions. Rice and other crops were identified as the main agricultural income sources of clusters 1–3, whereas rice, jute, chili, onion and other crops were those of cluster 4. The selected clusters produced the significant differences among the regions. In addition, rice predominated in cluster 2, while other crops predominated in cluster 3. These findings imply, for example, that rice is the main agricultural income source in Rangpur and Sylhet, while other crops are those in Chittagong and Comilla.

4.3. Reasons for Broad Income Distribution within a Region

To grasp the diversity of income for sampled farm households, the income can be decomposed into seven broad components, such as Agriculture, Fish, Livestock and poultry, Nonagricultural enterprise profit, Remittance, Other income and Employment income, in each region. We applied decomposition of variances and the results are shown in Table 6. The decomposition of variances is useful in evaluating how much each source of income contributes to total income variation of farm households. The decomposed variance share was derived from annual per capita income from the seven aforementioned broad income source sectors. Across Bangladesh, differences in remittances, other income and employment are important factors that all contribute the largest share of variation in total income. If a family can find good employment both inside and outside its region, it can become relatively wealthy, although income share from employment does not significantly more contribute in all regions (Table 6).

Table 6. Share of broad income components (%) in total income variation, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(b)	6.57	1.67	1.94	4.19	8.18	13.87	3.18	20.59	2.49	4.79
V(c)	20.03	0.19	0.03	1.57	35.73	8.17	1.11	0.23	1.98	6.42
V(d)	1.08	0.18	0.17	0.87	1.78	4.58	2.81	0.98	1.05	1.54
V(e)	17.39	13.64	6.33	16.50	13.47	11.90	5.09	7.84	19.73	11.63
V(f)	8.70	40.78	54.36	10.94	10.22	12.99	1.61	30.23	29.95	17.78
V(g)	4.84	0.05	14.76	1.16	0.61	2.38	69.70	0.37	2.82	21.63
V(h)	19.44	27.29	11.61	44.54	17.17	25.26	7.16	38.32	21.01	22.05
2*Cov(e,h)	21.95	15.22	10.81	20.22	12.85	14.22	7.32		20.96	14.16
2*Cov(b,c)								1.43		
2*Cov(c,h)							2.03			
2*Cov(f,g)		0.99								
2*Cov(c,e)						6.63				
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh; b = Agriculture, c = Fish, d = Livestock and poultry, e = Nonagricultural enterprise profit, f = Remittance, g = Other income and h = Employment income.

We found in Table 6 that agriculture is one of the main contributors to income differences in Mymensingh and Rangpur regions. Figure 4 shows total income distribution by income sources for the whole country, of which 22% of income inequality of total income is explained by inequality of employment income, while 13.87% and 20.59% of income inequality of total income explained by agriculture in Mynemnsingh and Rangpur respectively (Figures 5 and 6). Furthermore, this result indicates that remittance is the most important sector inducing income disparity in Comilla, compared to employment in Dhaka and Rangpur. In addition, other income sources are significant sources of income to confirm the total income disparity in Rajshahi. This finding likely explains that the income inequality of total income makes the larger contribution of inequality in agricultural income for crop farm households in Bangladesh.

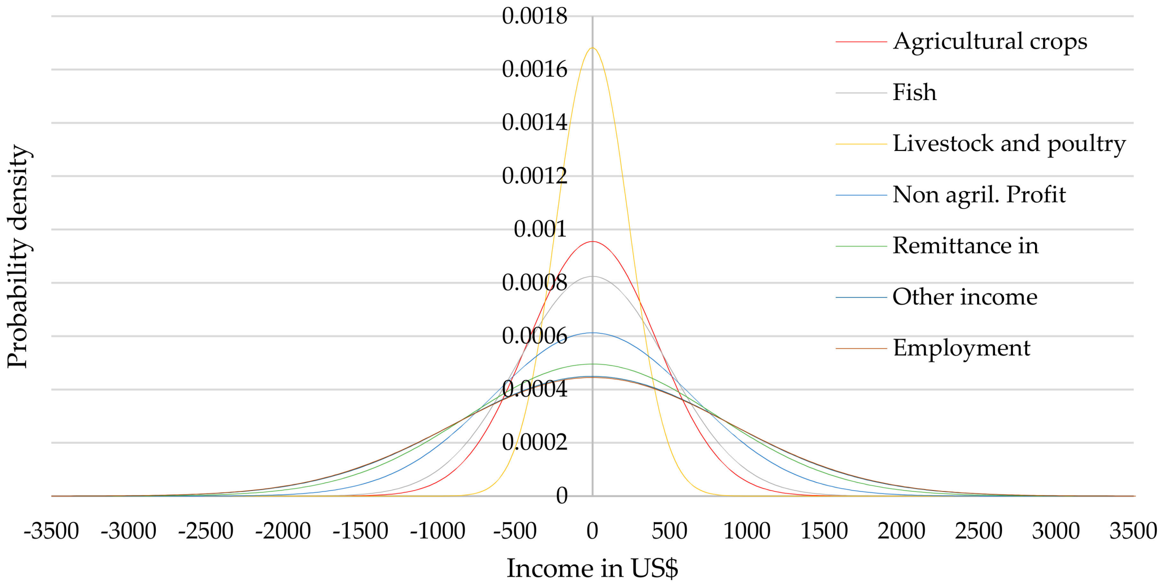

Figure 4. Distribution of total income for farm households in Bangladesh by income sources.

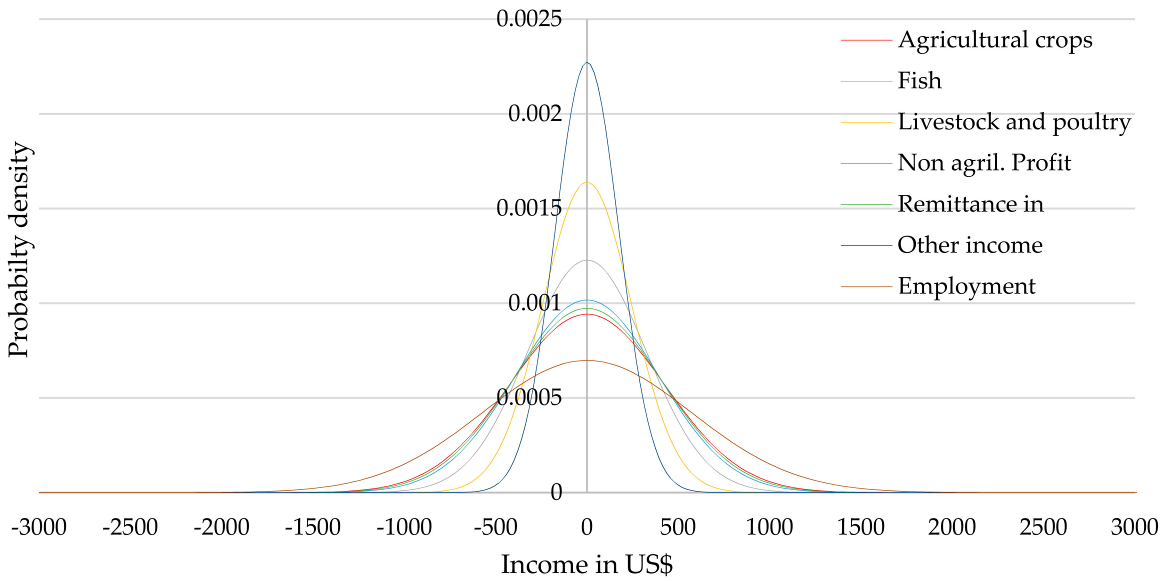

Figure 5. Distribution of total income (US$) for farm households in Mymensingh by income sources.

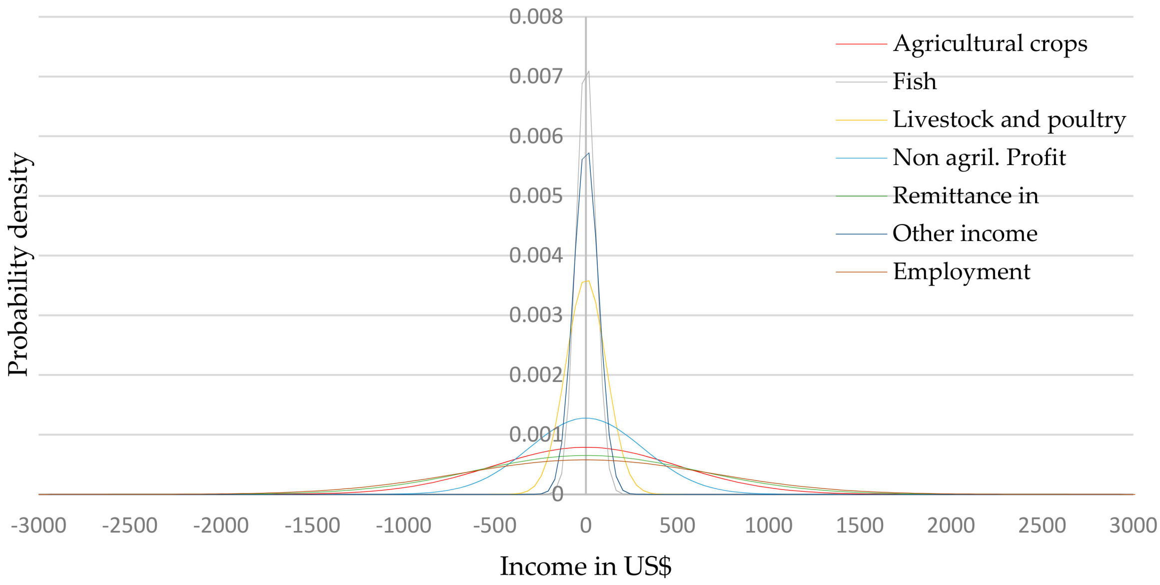

Figure 6. Distribution of total income (US$) for farm households in Rangpur by income sources.

4.4. Factors in Agricultural Income Differences

The main factors of agricultural income differences are shown in Table 7 obtained by the decomposed variance method. We estimate the variance component shares of crops for all farms across nine regions. From Table 6, we identify that agriculture is one of the main reasons for income differences in Mymensingh, Rangpur, Barisal, Khulna and Rajshahi. The empirical estimates of Table 7 indicate that the main variation in agricultural income comes from *aman* HYV (g) and *boro* HYV (j) rice. However, the results also display the contributions of other crop income to total agricultural income variation.

Table 7. Shares of crop income (%) in total agricultural income variation, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(b)	0.35	0.07	0.03	0.15	0.10	0.00	0.01	0.00	0.36	0.11
V(c)	0.08	0.04	0.03	0.00	0.00	0.06	0.06	0.01	0.04	0.04
V(d)	0.64	0.43	0.01	0.02	1.54	0.06	0.13	0.13	1.06	0.53
V(e)	5.23	0.00	0.36	0.36	0.53	0.50	0.50	0.15	2.06	1.02
V(f)	0.47	0.02	0.16	0.02	0.07	0.06	0.01	0.15	0.00	0.10
V(g)	8.95	7.67	1.12	1.63	10.15	3.84	7.64	12.95	7.88	8.50
V(h)	0.02	0.00	0.00	0.00	0.09	0.09	0.05	0.11	0.00	0.06
V(i)	0.70	0.00	0.06	0.01	0.06	0.00	0.00	0.36	0.16	0.14
V(j)	6.36	4.32	8.13	34.03	17.72	20.89	17.72	14.03	48.26	25.30
V(k)	2.49	2.13	1.26	5.71	3.88	0.69	3.56	3.40	17.82	5.03
V(l)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
V(m)	0.00	0.00	0.01	0.04	0.15	0.00	0.23	0.18	0.00	0.11
V(n)	0.00	0.00	0.27	0.07	0.10	0.00	0.53	0.65	0.00	0.28
V(o)	0.26	0.00	4.28	4.74	2.46	0.04	0.91	0.93	0.14	2.38
V(p)	0.49	0.04	20.77	0.35	0.03	0.08	1.78	6.48	0.16	2.68
V(q)	1.65	0.90	0.81	11.56	12.40	0.98	0.17	0.49	0.08	6.00
V(r)	0.00	0.00	0.00	6.51	0.54	0.00	0.63	0.02	0.00	1.91
V(s)	67.37	75.85	43.55	29.35	44.77	62.62	16.16	24.67	21.98	44.00
2*Cov(o,r)				5.43	0.85		0.81			1.79
2*Cov(g,j)		5.75				9.73	11.64	13.34		
2*Cov(g,k)		2.79			0.37		4.55	7.94		
2*Cov(g,p)						0.02	3.58	11.66		
2*Cov(o,p)			18.45			0.34	6.19	2.33		
2*Cov(g,s)							9.54			
2*Cov(j,s)							13.61			
2*Cov(d,j)	4.95		0.72		4.20					
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet, BD = Bangladesh; b = *Aus* rice local, c = *Aus* rice LIV, d = *Aus* rice HYV, e = *Aman* rice Local, f = *Aman* rice LIV, g = *Aman* rice HYV, h = *Aman* rice Hybrid, i = T *Aus* rice HYV, j = *Boro* rice HYV, k = *Boro* rice Hybrid, l = Wheat Local, m = Wheat HYV, n = Maize, o = Jute, p = Potato, q = Chili, r = Onion, s = All other crops.

Rice is the leading crop in Bangladesh, accounting for more than 90% of total cereal production covering 75% of Bangladesh's total cropped area [45,69]. For Mymensingh and Rangpur, variances in both *aman* HYV and *boro* HYV rice are high. For other regions, variances in *boro* HYV are high.

All other crops(s) are among the main causes (44% variance share) of income differences for all of Bangladesh since all types of pulses, oil seeds, spices, vegetable, leafy vegetables and fruits are included in the group of "all other crops." Moreover, all other crops(s) explain the larger contribution to total agricultural income variation because, in some regions, vegetables and fruits, among others, excluding rice, are important agricultural income sources.

The distribution of crop income among total agricultural income for the whole country is shown in Figure 7, which follows in Figures 8 and 9 for Mymensingh and Rangpur, respectively, with selected crops mainly produced by farmers in these regions. We found that *boro* rice has the widest variation in both the region and the highest inequality of total agricultural income, explained by the inequality of *boro* HYV income.

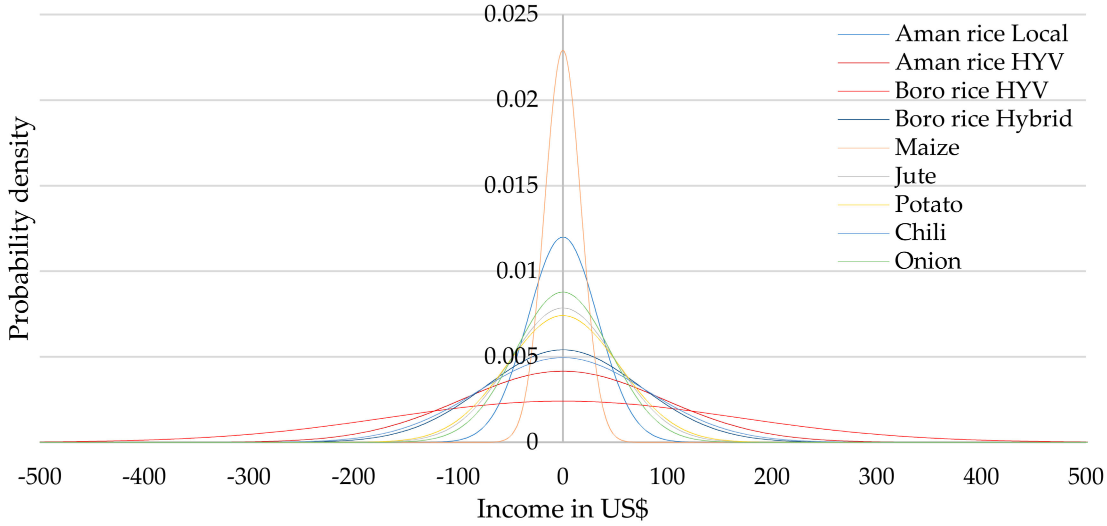

Figure 7. Distribution of agricultural income for farm households in Bangladesh by crop income.

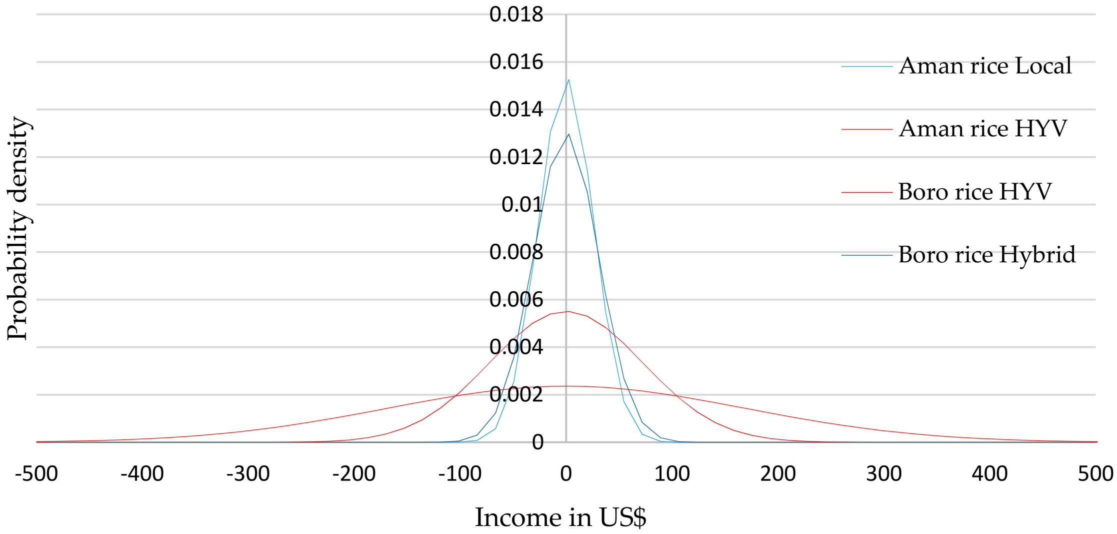

Figure 8. Distribution of agricultural income for farm households in Mymensingh by crop income.

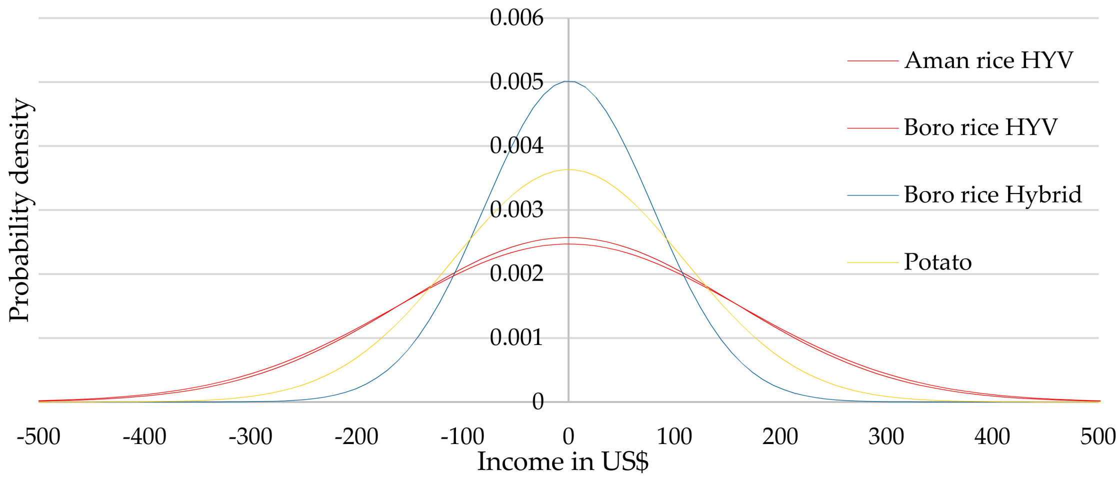

Figure 9. Distribution of agricultural income (US$) for farm households in Rangpur by crop income.

4.5. Factors Contributing to Variations in Income from Aman HYV and Boro HYV Rice Production

According to the results of Table 7, it is important to determine the factor causing the net income differences in *aman* HYV production. From decomposed variance of gross income and gross cost, we find in Table 8 that gross income is the main factor in net income difference, indicating that, although farmers in same region cultivated *aman* HYV rice, their gross incomes were different.

Table 8. Decomposed variances share (%) of GI and GC for *aman* HYV rice, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(GI)	75.31	74.34	98.38	53.87	76.53	57.17	66.88	74.25	45.49	69.45
V(GC)	80.97	33.57	35.80	91.18	36.13	49.23	55.56	30.27	55.10	45.67
−2*Cov(GI, GC)	−56.27	−7.91	−34.18	−45.06	−12.66	−6.39	−22.44	−4.52	−0.59	−15.11
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh; GI = Gross income; and GC = Gross cost.

These gross income differences mainly induce the net income disparities in Comilla, Khulna, Chittagong and Rangpur, while gross cost induces the income disparities in Dhaka and Barisal for *aman* HYV rice. Additionally, gross cost also contributes to the total net income disparity of *aman* HYV rice production. To determine the variance in gross cost for *aman* HYV rice production, we estimate the variance component shares of all costs contributing to gross cost and present them in Table 9.

The results show the factors responsible for large variations in cost from *aman* HYV rice production. As shown in Table 9, variances in seed (c) shows in third row, chemical fertilizer (g) in row seven and hired labor costs (k) in row eleven, are high across all regions. In Dhaka, the highest 80% of inequality of gross cost for *aman* HYV rice production is explained by the inequality of hired labor cost (k), while in Barisal, the highest 25% inequality of gross cost is explained by inequality of seed cost. These costs were the main factors inducing the income differences in *aman* HYV rice production. This result indicates the importance of farming knowledge and easy input access to rice cultivation.

Table 9. Decomposed variances share (%) of costs for *aman* HYV rice production, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(b)	3.64	3.73	3.79	0.97	3.66	5.50	3.72	8.79	4.32	3.24
V(c)	25.01	1.87	24.54	1.47	3.55	5.56	3.12	6.78	3.81	5.15
V(d)	0.53	1.79	1.04	1.32	8.33	2.04	4.15	6.70	0.67	3.69
V(e)	0.07	0.18	0.19	0.08	0.41	0.64	0.77	0.64	0.23	0.33
V(f)	0.54	0.48	0.28	0.07	0.65	0.10	0.65	0.54	0.14	0.35
V(g)	5.32	9.73	6.27	1.54	12.74	6.72	7.57	7.05	3.38	6.42
V(h)	0.98	0.06	0.01	0.04	0.30	2.76	0.05	0.57	1.42	0.50
V(i)	9.49	2.29	1.88	0.35	4.25	1.29	1.31	2.70	1.62	2.10
V(j)	3.47	0.58	1.62	0.10	0.44	0.70	0.15	0.26	3.04	0.69
V(k)	15.16	39.90	45.37	80.58	37.61	70.65	40.88	58.04	74.50	59.53
2*Cov(f,g)	1.72	2.37	1.33	0.33	2.14	0.77	3.05	1.26		1.41
2*Cov(i,f)	2.07		0.59	0.13			1.17	1.03	0.41	0.54
2*Cov(i,g)	11.50		3.88	0.77	5.69	3.26	4.29	4.69	1.94	3.32
2*Cov(k,g)	5.46	20.32		8.55	19.47		18.35			12.74
2*Cov(c,j)	15.04							0.95	4.52	
2*Cov(k,f)		3.79		2.04			4.82			
2*Cov(k,i)		1.90	9.21	1.67	0.75		5.94			
2*Cov(c,k)		11.0								
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal; CH = Chittagong; CO = Comilla; D = Dhaka; K = Khulna; M = Mymensingh; RJ = Rajshahi; RN = Rangpur; S = Sylhet; and BD = Bangladesh; b = Rental cost of land; c = Seed cost; d = Irrigation cost; e = Manure/compost cost; f = Pesticide cost; g = Chemical fertilizer cost; h = Draft animal cost for land preparation; i = Rental cost for tools and machinery; j = Threshing cost; and k = Hired labor cost.

In Table 7, we note that *boro* HYV also had an influence on agricultural income. It is essential to determine the factors affecting the net income variation for *boro* HYV rice cultivation. Table 10 summarizes the decomposed variance of gross income and gross cost from *boro* HYV rice production and shows that gross income is the main factor in net income differences for *boro* HYV rice production, except for in Chittagong and Sylhet. However, gross cost also contributes to the total net income disparity of *boro* HYV rice production.

Next, we want to know which costs are the main factors in income differences in *boro* HYV rice production. To know the variance in gross costs for *boro* HYV rice production, we estimate the variance component shares of all cost expenditures contributing to gross cost and present them in Table 11. We found that the variances in seed (c) shows in third row, irrigation (d) in row four, chemical fertilizer (g) in row seven and hired labor cost (k) in row eleven, are high in all regions, indicating that adaptation strategies, such as low input costs, have priorities for the large gross income variances of *boro* rice cultivation.

Table 10. Decomposed variance share (%) of gross income and cost of *boro* HYV rice, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(GI)	101.34	46.75	264.6	62.73	79.59	70.15	69.81	80.61	67.68	91.68
V(GC)	43.86	79.49	97.26	41.17	40.46	47.38	60.96	28.25	84.98	54.04
−2*Cov (GI, GC)	−45.20	−26.24	−261.9	−3.90	−20.05	−17.53	−30.77	−8.86	−52.66	−45.72
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh; GI = Gross income and GC = Gross cost.

These input costs were made the net income differences in this rice production for sample farmers. Based on the findings in Table 11, it is also important to note that, in Chittagong region, the variance in hired labor cost (k) is highest (69.84%) while it is lowest in Comilla region (27.25%). This result implies that 69.84% of inequality of gross cost is elucidated by the inequality of hired labor cost in Chittagong region. As shown in the fourth row, irrigation cost (d) contributes a significant share of the variation of gross cost; the highest 22.93% of inequality of gross cost is explained by the inequality of irrigation cost in Dhaka, compared to the lowest in Chittagong. This result implies that reduction of input cost variances will ensure the low net income differences for this rice production. Farm households are not entirely self-sufficient regard the labor supply for their farming. In peak times of agricultural production, such as transplanting, weeding and harvesting, hired labor demand occurs. However, the labor supply is low in Chittagong due to hill tract areas of Bangladesh [69], resulting in the higher costs of labor.

Table 11. Decomposed variance share (%) of costs for *boro* HYV rice production, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
V(b)	2.87	0.66	0.50	1.88	2.66	4.11	1.32	5.32	2.63	2.27
V(c)	4.10	0.71	2.21	3.67	4.78	2.72	1.73	4.34	2.20	3.61
V(d)	8.89	2.70	4.06	22.93	22.39	22.42	10.70	16.00	7.57	18.01
V(e)	0.24	0.05	1.10	0.31	0.76	0.88	0.33	2.56	0.12	0.80
V(f)	0.89	0.09	0.18	0.16	0.48	0.33	0.31	0.60	0.07	0.33
V(g)	7.71	3.31	1.98	6.71	14.76	12.82	4.71	13.54	3.23	8.21
V(h)	0.04	0.03	0.00	0.05	0.79	10.08	0.13	0.38	2.04	1.16
V(i)	2.42	0.89	1.01	0.93	1.47	1.09	0.47	1.68	1.12	1.23
V(j)	0.98	0.20	0.15	1.08	0.75	2.24	0.24	0.39	0.18	0.78
V(k)	38.05	69.84	27.25	42.04	38.45	31.49	51.04	38.17	65.10	51.51
2*Cov(f,g)	3.91	0.73	0.66	0.90	2.15		1.49	3.46	0.50	1.55
2*Cov(d,g)	4.98		1.18				4.35			
2*Cov(f,i)	1.07	1.15	2.62	0.39	0.52		0.52	0.97	0.26	0.61
2*Cov(g,i)	4.68	2.70	1.99	2.87	5.47	3.76	2.14	5.69	1.99	3.43
2*Cov(g,k)	11.72	14.45	6.27	11.25			10.64		11.72	
2*Cov(i,k)	7.46		6.84	4.83	4.58	8.05	3.89			5.90
2*Cov(e,i)		2.50	9.58					1.25	0.22	0.60
2*Cov(f,k)			5.34				5.99			
2*Cov(e,g)			1.50					4.90	0.44	
2*Cov(e,f)			7.04					0.76	0.63	
2*Cov(d,k)			8.70							
2*Cov(e,k)			9.85							
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh; b = Rental cost of land, c = Seed cost, d = Irrigation cost, e = Manure/compost cost, f = Pesticide cost, g = Chemical fertilizer cost, h = Draft animal cost for land preparation, i = Rental cost for tools and machinery, j = Threshing cost and k = Hired labor cost.

4.6. Future Projections

Production levels in agriculture, fishery and livestock raising are projected to change due to climate change [39,83]. We therefore sought to project the impact of rice yield change on the state of poverty in Bangladesh. If rice is a commercial crop, a price hike due to any damage from climate change could increase Bangladeshi farmers' living standards. However, rice remains a subsistence crop among most Bangladeshi farmers; therefore, we assume that rice yield reduction will lead to a rice consumption reduction.

The effects of climate change on rice yields, as has been estimated and shown by International Food Policy Research Institute [37], are such that, without adaptation to climate change impacts, *aman* HYV and *boro* HYV rice yields will decline by 3.5% and 10.2%, respectively, in Bangladesh. According to the Geophysical Fluid Dynamics Laboratory (GFDL) scenarios, if temperature changes by 4.0 °C, then 17% decline in overall rice will occur in Bangladesh [84].

According to this projection, we assumed that, due to climate change effects on *boro* HYV and *aman* HYV, rice yields will be reduced by 10% and 4%, respectively, as well as a 17% reduction in overall rice among the sample households. We applied log-normal distribution to project the poverty rate due to income reduction by yield loss on the effects of climate change.

Figure 10 shows the annual per-capita income (actual and projected) in US$ of the sample households across Bangladesh. In general, one can see from this figure that the sample population density (i.e., probability density) mostly lies within the low annual per-capita income range, which is less than the poverty line. Additionally, the probability density of the low-income range increases in the projected income distribution when one considers rice yield loss due to climate change.

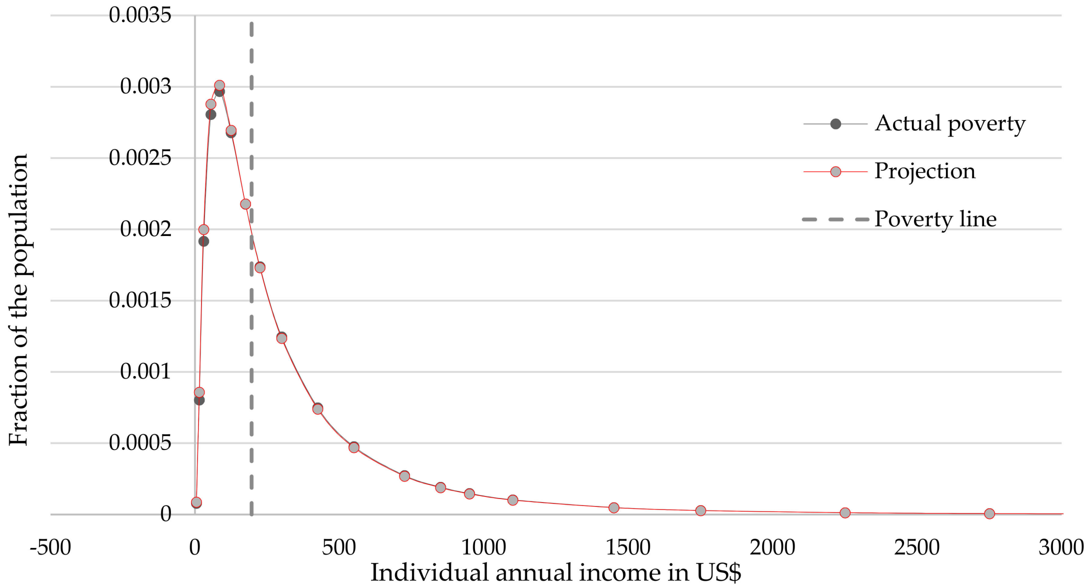

Figure 10. Annual per-capita income (US$) distribution of Bangladesh (17% loss of rice).

From the decomposed variance share of income sources in Table 9, we found that agriculture was the main reason for income differences in Mymensingh and Rangpur. Now, we can examine the effects of climate change on rice production (10% and 17% losses) in these two regions by log-normal distribution.

We analyzed and found that constant reduction of rice yield (10% loss) by climate change in Bangladesh is not such a severe problem for farmers. Because the change in net per-capita income is very small, there is not a dramatic change of poverty rate. However, if unexpected extreme events, such as floods, flash floods, droughts and sea level rise, occur in specific areas of Bangladesh, they create a more vulnerable situation for the farmers' livelihood. In addition, the probability density of low-income range increases (Figures 11 and 12) in both Mymensingh and Rangpur districts, where rice income decreases due to climate change.

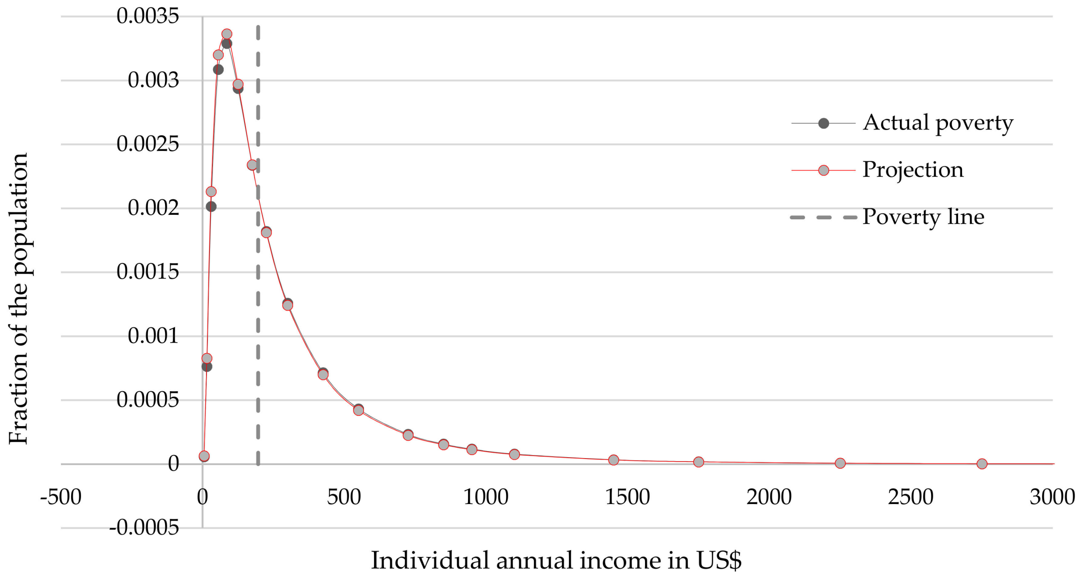

Figure 11. Annual per-capita income (US$) distribution of Mymensingh (17% loss of rice).

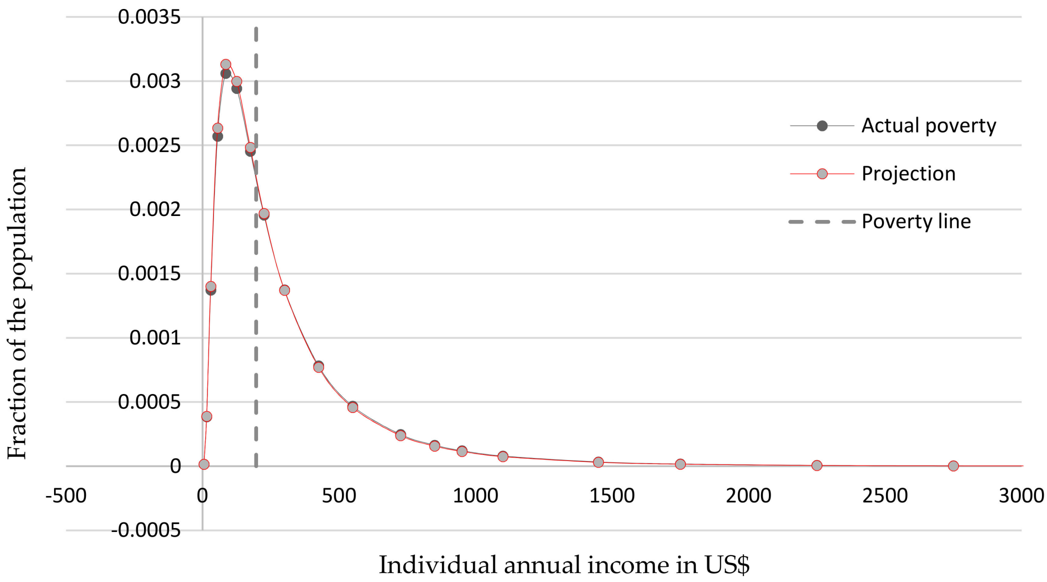

Figure 12. Annual per-capita income (US$) distribution of Rangpur (17% loss of rice).

We also applied the same analysis in Figures 10–12 to all of the regions and Table 12 shows the results of the poverty rate after income changes due to assumed yield losses of *aman* HYV, *boro* HYV rice and overall rice.

Table 12. Change in poverty rate following a loss of rice yield due to climate change.

		B	CH	CO	D	K	M	RJ	RN	S	BD
	Actual	0.507	0.484	0.446	0.455	0.415	0.496	0.323	0.462	0.484	0.454
10% loss	Projected	0.508	0.491	0.447	0.458	0.417	0.502	0.330	0.466	0.487	0.457
	Change	0.001	0.007	0.001	0.003	0.002	0.006	0.007	0.004	0.003	0.003
	Increase (%)	0.197	1.446	0.224	0.659	0.482	1.210	2.167	0.866	0.620	0.661
17% loss	Projected	0.513	0.494	0.449	0.460	0.422	0.511	0.335	0.473	0.490	0.461
	Change	0.006	0.010	0.003	0.005	0.007	0.015	0.012	0.011	0.006	0.007
	Increase (%)	1.183	2.066	0.673	1.099	1.687	3.024	3.715	2.381	1.240	1.542

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh.

The estimated results suggest that rice yield loss would reduce the annual per-capita income of the sample farm households and increase the poverty rate in various regions across Bangladesh. It was found that the highest poverty rate increase (3.024%) would occur in Mymensingh, Rajshahi (3.715%) and Rangpur (2.381%). Rajshahi and Rangpur are in northwestern Bangladesh and are prone to drought; climate change would affect rice production specifically in the summer, when *boro* rice is being produced. Mymensingh is affected by floods, flash floods and heavy rainfall each year, owing to the effects of climate change on *aman* and *boro* harvests.

Climate Change Impact Scenario

Extreme events, such as floods, droughts and changes in seasonal rainfall patterns, negatively impact crop yields in vulnerable areas [85–87]. In Bangladesh, the rural poverty rate would be exacerbated [88] as a result of the impacts of extreme events on the yield of rice crop and increases in food prices and the cost of living [89,90]. The impacts of climate change on poverty would be heterogeneous among countries [91]. Due to the impact of climate change, rice production would decrease and some rice exporting countries, such as Indonesia, the Philippines and Thailand, would benefit from global food price rises and reduced poverty, while Bangladesh would experience a net increase in poverty of approximately 15% by 2030 [89,91].

Climate change refers to changes in climate attributed directly as temperature, precipitation, CO_2 concentrations and solar radiation or indirectly as river floods, flash floods and sea level rise that alter the composition of the global atmosphere, as well as to natural climate variability observed over comparable time periods [33,50].

Temperature Increase

Temperature is an important factor for *boro* rice production and the maximum temperature is always more vulnerable with a negative impact on rice yields. In Bangladesh, seasonal temperature suddenly fluctuates, causing drastically declines in the yield of *boro* rice. *Boro* rice yields decrease by a maximum of 18.7% due to an increase in minimum temperature of 2.0 °C–4.0 °C and by 36.0% for 2.0 °C–4.0 °C maximum temperature increases in different location of Bangladesh in 2008 [92]. According to the Intergovernmental Panel on Climate Change (IPCC), SRES emissions scenarios and climate models being considered, global mean surface temperature is projected to rise in the range of 1.8 to 4.0 °C by 2100 [93]. Following the previous assessment, the IPCC concludes in their fifth assessment report (AR5) that it will be difficult to adapt with large-scale warming of approximately 4°C or more, which will increase the likelihood of severe, pervasive and irreversible impacts [91,94,95].

According to the previous projection of temperature fluctuations in Bangladesh, we assume that, due to the maximum and minimum temperature fluctuations, in the future, the overall rice production will decrease by approximately 17% of the sample farmers and results are shown in Table 12. The table shows that maximum 3.7% poverty will increase in Rajshahi and second highest (3.0%) in Mymensingh region and this implies that it is important to adaptation strategies for Rajshahi and Mymensingh for high temperature.

Rainfall Decreases (Drought)

Inadequate rainfall leads to greater drought frequency and intensity, while increased evaporation increases the chance of complete crop failure [96,97]. Drought is the most widespread and damaging of all environmental stresses [35,98]. In South and Southeast Asia, including some states of India, severe drought affects rain-fed rice and yield, with losses as high as 40% and the total area affected measuring 23 million hectares, amounting to $800 million [99]. Bangladesh experienced severe drought in different years and locations in the districts of the northwestern border [100]. Erratic rainfall and drought reduce crop production by 30% and 40%, respectively [84]. *Boro* rice production will decrease due to rainfall in winter [92]. This study noted that, with 5-mm and 10-mm rainfall reductions in the future, *boro* rice will decrease by a maximum of 16.6% and 24.2%, respectively, in the winter. Drought caused 25% to 30% crop reduction in the northwestern part of Bangladesh based on from 2008 [101]. Due to the high rainfall variability and dryness, the northwestern region is the most drought-prone area in Bangladesh [102,103]. Rajshahi, Chapai-Nawabganj, Naogaon, Natore, Bogra, Joypurhat, Dinajpur and Kustia districts are drought prone areas in Bangladesh because of their moisture-retention capacity and infiltration rate characteristics [104].

According to the previous projection of drought, we assume that, if rainfall decreases and drought occur in the future, the overall rice production will decrease by approximately 20% of the sample farmers in northwestern districts of Bangladesh. By using log-normal distribution, we project the poverty rate due to income reduction by yield loss because of drought.

Table 13 shows the results of the poverty rate (Figure 13) after income changes due to assumed yield losses of overall rice by drought in the northwestern region in Bangladesh, while the Dinajpur (10.175% poverty increase), Rajshahi (5.670% poverty increase) and Naogaon (11.245% poverty increase) districts are most vulnerable to poverty. Dependency on agriculture with high variability of annual rainfall has made the northwestern regions highly susceptible to droughts and high poverty rates, compared to other parts of the country. Conservation of water could play an important role in reducing the impact of drought and alleviating poverty in this area [103].

Table 13. Poverty rate in drought-prone districts on rainfall decrease.

	BG	CN	DI	KU	NG	NT	RJ	JT
Actual	0.242	0.354	0.285	0.447	0.249	0.448	0.388	0.268
Projected	0.263	0.361	0.314	0.452	0.277	0.452	0.410	0.282
Change	0.021	0.007	0.029	0.005	0.028	0.004	0.022	0.014
Increase (%)	8.678	1.977	10.175	1.119	11.245	0.893	5.670	5.224

BG = Bogra, CN = Chapai-Nawabganj, DI = Dinajpur, KU = Kustia, NG = Naogaon NT = Natore, RJ = Rajshahi and JT = Joypurhatr.

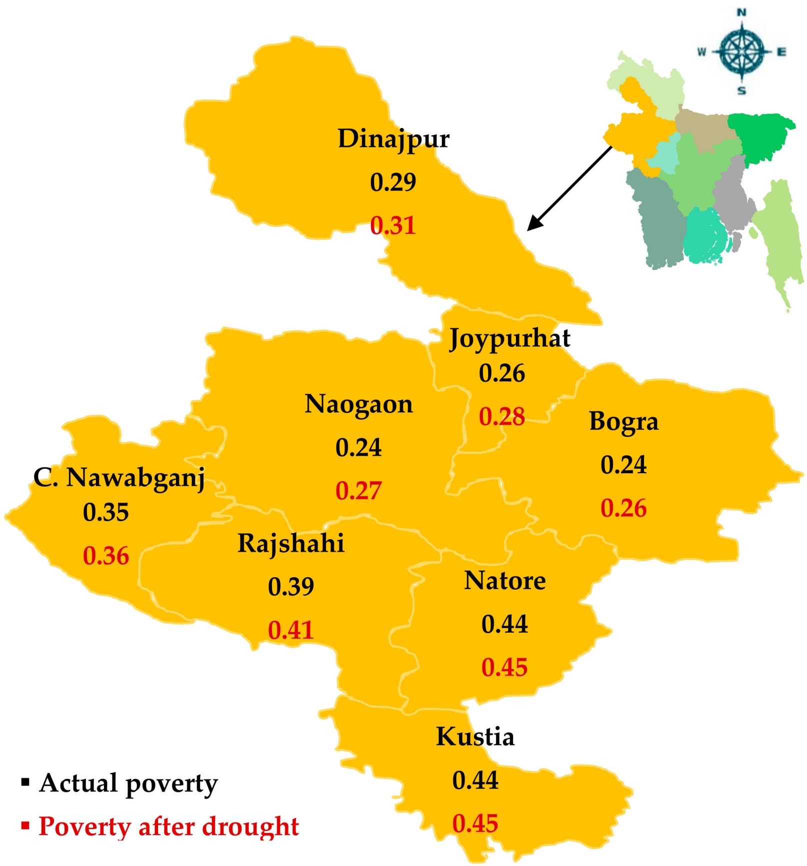

Figure 13. Changing poverty rates caused by drought in northwestern regions.

Flood

From the GBM basins, the monsoonal discharge of water causes seasonal floods and affects most of the areas of Bangladesh, with extent varying by year [50]. Floods occur almost every year and in 1998, floods covered almost 70% of total land area in Bangladesh, causing the maximum damage by floods in Bangladesh [105]. According to the IPCC's fourth assessment report, the intensity and frequency of floods and cyclones will increase in the near future [33]. Moreover, the IPCC's fifth assessment report (AR5) predicts that greater risks of flooding will increase on the regional scale [91,94–99]. In addition, extreme flood events will reduce crop production by 80% in Bangladesh [37,84].

Mymensingh, Sylhet, Dhaka, Comilla, some parts of Rangpur and Khulna regions are the mainly river-flooded areas in Bangladesh [50]. We assume that, if extreme floods, as in 1998 (the magnitude of the 1998 flood was the maximum in Bangladesh), occur, farm production will decrease by 80% in the flood-prone regions of Bangladesh. By log-normal distribution we project the poverty rate due to income reduction by yield loss due to the effects of extreme floods. The results are shown in Table 14.

Table 14. Poverty rate due to yield loss by flood in Bangladesh.

	CO	D	K	M	RN	S
Actual	0.446	0.455	0.415	0.496	0.462	0.484
Projected	0.465	0.502	0.479	0.554	0.529	0.519
Change	0.019	0.047	0.064	0.058	0.067	0.035
Increase (%)	4.260	10.330	15.422	11.694	14.502	7.231

CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RN = Rangpur and S = Sylhet.

The estimated results in Table 14 suggest that rice yield loss would reduce the annual per-capita income of the sample farm households and increase the poverty rate in various regions across Bangladesh (Figure 14). It was found that the highest poverty rate increases would occur in Rangpur (14.502%) and Khulna (15.422%). This result implies that coping strategies to highly flood affected areas of crops loss should have priority.

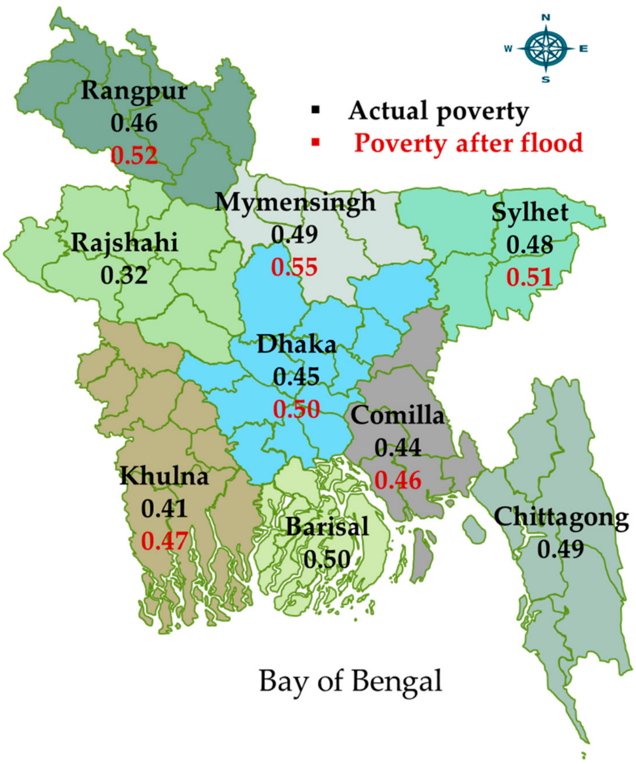

Figure 14. Changing poverty rates caused by floods in different regions.

Flash Floods

The northeastern parts of Bangladesh—mostly Sunamganj, Kishorganj, Netrokona, Sylhet, Habiganj and Maulvibazar—are prone to flash floods during the months of April to November and these areas are covered by many haors, where water remains stagnant [106]. Farmers of these districts produced *boro* rice in almost 80% of their land, while only approximately 10% of the area is covered by transplanted *aman* production [107]. In 2017, flash floods affected these areas and damaged almost 90% (maximum) of *boro* rice [108]. According to this scenario, we assumed that if in the future this extreme event occurs in haor areas, *boro* rice yields will be reduced by a maximum of 90% of the sample households. We applied log-normal distribution to project the poverty rate due to income reduction by yield loss due to the effects of flash floods on *boro* rice yields by a maximum of 90%.

Table 15 shows the results of the poverty rate after incomes changed due to assumed yield loss of *boro* rice in flash flood regions in Bangladesh, while Kishorganj district is most vulnerable to poverty

(19.214% increase) if flash floods occur (Figure 15). The projected results are treated as flash flood to be changed the poverty in northern-eastern parts of Bangladesh and this region are vulnerable on flash flood. Therefore, ex-ante coping strategies are important to the damages of flash flood.

Table 15. Poverty rate in flash flood region in Bangladesh.

	HB	KI	MV	NT	SU	SY	TH
Actual	0.354	0.458	0.624	0.585	0.511	0.427	0.354
Projected	0.381	0.546	0.637	0.628	0.550	0.452	0.381
Change	0.027	0.088	0.013	0.043	0.039	0.025	0.027
Increase (%)	7.627	19.214	2.083	7.350	7.632	5.855	7.627

HB = Habiganj, KI = Kishorganj, MV = Maulvibazar, NT = Netrokona SU = Sunamganj, SY = Sylhet and TH = Total Haor.

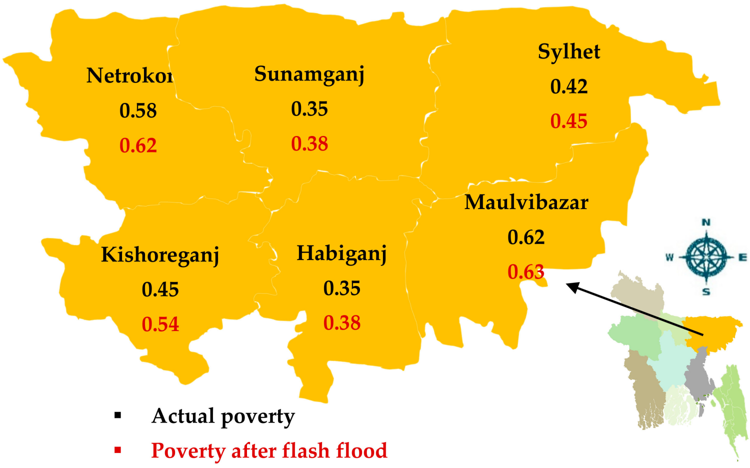

Figure 15. Changing poverty rate caused by flash floods in northeastern regions.

Sea Level Rise

Approximately 80% of the land of Bangladesh is flatlands, while 20% is 1 m or less above sea level, which is the coastal area (southern 19 districts beside the Bay of Bengal) and particularly vulnerable to sea level rise [109]. The coastal area covers approximately 20% of the country (including 19 districts beside the Bay of Bengal), which is approximately 30% of the net cultivable area and 25.7% of the population of Bangladesh [110,111]. Sea level rise will directly result in increased coastal flooding, which will increase in the event of storm surges. IPCC's fourth assessment report [33] reports that a 1-m sea level rise will displace approximately 14,800,000 people by inundating a 29,846-sq. km. coastal area [112]. Nicholls and Leatherman in 1995 [113] predicted that a 1-m sea level rise would result in a 16% of national rice production loss in Bangladesh [114].

In terms of number of people affected with respect to sea level rise, Bangladesh has been rated as the third most vulnerable country in the world. By 2050, approximately 33 million people would be suffering from surging, assuming a sea level rise of 27 cm. A full 18% of the total land area in Bangladesh would submerge with a 1-m rise in sea level [115]. Based on the IPCC fifth annual report (AR5), across all representative concentration pathways (RCPs), global mean temperature (°C) is projected to rise by 0.3 to 4.8 °C by the late-21st century and global mean sea level (m) is projected to increase by 0.26 to 0.82 m [91]. The Global Circulation Model (GCM) predicts an average temperature increase of 1.0 °C by 2030, 1.4 °C by 2050 and 2.4 °C by 2100; the study revealed that the sea level will rise by 14 cm, 32 cm and 62 cm, respectively. A rise in temperature would cause significant decreases in production of 28 % and 68 % for rice and wheat, respectively [84].

According to this scenario, we assumed that, due to sea level rise in the southern part of Bangladesh, *boro* rice yields will be reduced by 30% of the sample households. We applied log-normal distribution to project the poverty rate due to income reduction with yield loss based on the effects of sea level rise.

Table 16 shows the results of the poverty rate after income changes due to assumed yield loss of rice in coastal regions due to sea level rise, while Khulna district is the most vulnerable to poverty and poverty will increase by 6.752% (Figure 16). Changing continuous sea level rise in the coastal region result in no significant loss reduction for rice.

Table 16. Poverty rate in sea level rise regions in Bangladesh.

	SK	KH	BT	PR	JL	BG	BS	PT	BL	LK	NK	FN	CT	CX
Actual	0.599	0.295	0.363	0.388	0.640	0.532	0.419	0.628	0.491	0.529	0.438	0.481	0.505	0.462
Projected	0.609	0.315	0.370	0.390	0.650	0.545	0.431	0.636	0.493	0.533	0.440	0.487	0.515	0.464
Change	0.010	0.020	0.007	0.002	0.011	0.013	0.013	0.008	0.002	0.004	0.002	0.007	0.010	0.002
Increase (%)	1.688	6.752	1.924	0.527	1.674	2.388	3.081	1.255	0.491	0.770	0.410	1.361	1.901	0.367

SK = Satkhira, KH = Khulna, BT = Bagerhat, PR = Pirozpur, JL = Jhalakati, BG = Barguna, BS = Barisal, PT = Patuakhali, BL = Bhola, LK = Lakshmipur, NK = Noakhali, FN = Feni, CT = Chittagong and CX = Cox's Bazaar.

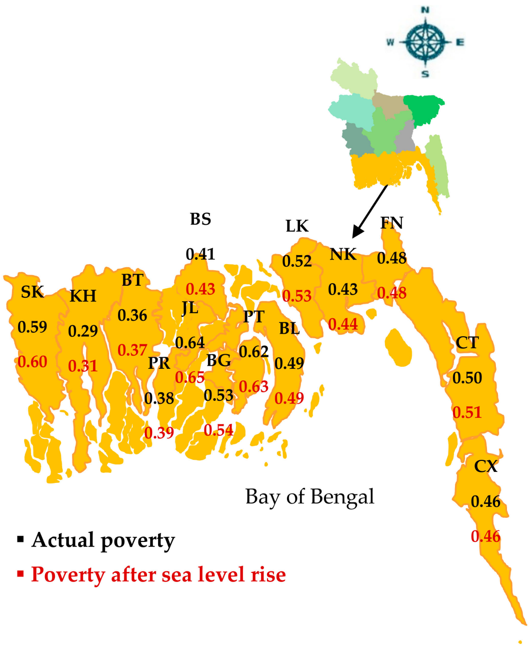

Figure 16. Changing poverty rate caused by sea level rise in southern regions.

Representative Concentration Pathways (RCPs)

In assessing future climate change, the fifth assessment report (AR5) of the IPCC selected four RCPs, –RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5 [91], with RCP 4.5 and RCP 8.5 covering both medium and extreme scenarios. These four RCPs describe four probable climate futures depending on how much greenhouse gasses are emitted over the next 85 years.

According to the IPCC's fifth annual report (AR5), across all representative concentration pathways (RCPs), global mean temperature (°C) is projected to rise by 0.3 to 4.8 °C by the late-21st century [68]. Increasing temperatures will increase the number of growing days over time. Heat stress is a major issue for crop production and reduces yields.

Climate change will certainly continue in coming decades and affect agricultural production. Yamei Li et al. worked on simulating total climate change impacts on rice production under RCP scenarios and projected that average rice yields during the 2020s, 2050s and 2080s would decrease by 12.3%, 17.2% and 24.5% under RCP 4.5 and by 14.7%, 27.5% and 47.1% under RCP 8.5, respectively [67].

According to this scenario, we assumed that, due to total climate change impacts, rice yields would be reduced by a maximum of 47% based on RCP 8.5 among the sample households. We applied log-normal distribution to project the poverty rate due to income reduction by yield loss. Table 17 shows that, under RCP 4.5 and RCP 8.5, the poverty rate will increase in all of the regions because of rice income reductions.

Additional increases in average poverty occur in Rajshahi, Mymensingh, Rangpur, Khulna and Sylhet region under both RCP 4.5 and RCP 8.5 with variations in the total climate change impacts on rice production. The yield of rice is predicted to decrease more under RCP 8.5 than RCP 4.5, resulting in per-capita income decreases. Under RCP 8.5, this study predicts a maximum increase in poverty of 10.526% in Rajshahi and the lowest of 3.139% in Comilla (Table 17). It is possible that our predicted rice yield declines by RCP scenario and relatively drought prone areas, such as Rajshahi, will be more vulnerable (Figure 17). The results from our drought scenarios are comparable to the results for RCP 8.5 and it is consistent that Rajshahi region is more vulnerable under climate change impacts. In both scenarios, our predicted yield decline and resulting per-capita income decline increase poverty. Climate change forces a decline in rice yield [116], suggesting that the predicted decreases in heat stress yield can be mostly attributed to an increased drought tolerant variety.

Table 17. Changes in poverty rates following a loss of rice yield due to RCPS.

		B	CH	CO	D	K	M	RJ	RN	S	BD
25% loss of rice under RCP 4.5	Actual	0.507	0.484	0.446	0.455	0.415	0.496	0.323	0.462	0.484	0.454
	Projected	0.516	0.490	0.455	0.462	0.424	0.510	0.345	0.471	0.497	0.463
	Change	0.009	0.006	0.009	0.007	0.009	0.014	0.022	0.009	0.013	0.009
	Increase (%)	1.775	1.240	2.018	1.538	2.169	2.823	6.811	1.948	2.686	1.982
47% loss of rice under RCP 8.5	Projected	0.524	0.500	0.460	0.470	0.438	0.526	0.357	0.488	0.507	0.474
	Change	0.017	0.016	0.014	0.015	0.023	0.030	0.034	0.026	0.023	0.020
	Increase (%)	3.353	3.306	3.139	3.297	5.542	6.048	10.526	5.628	4.752	4.405

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh.

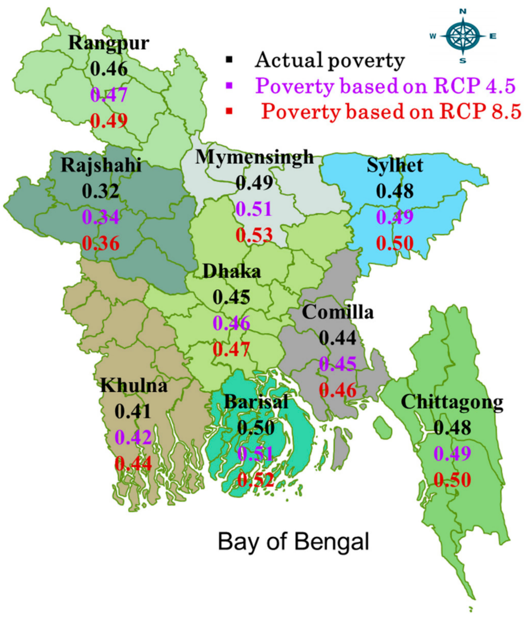

Figure 17. Changing poverty rate caused by total climate change impact based on RCP 4.5 and 8.5.

5. Conclusions

This paper has focused on the agrarian sub-national regional analysis of climate change vulnerability in Bangladesh under various climate change scenarios and its potential impact on poverty. It has drawn some significant evidence of regional vulnerability to climate change from regional characteristics, per-capita income, total income disparity, cost of production and poverty, based on statistical analysis of farm survey data. Our findings indicated that some regions are vulnerable to climate change impact on agricultural production among the administrative regions of Bangladesh, where coping strategies and techniques are important.

Bangladeshi farmers are producing crops, although there is much uncertainty due to associated risks of climate change. The results of our study show that, from the income shares of income source sectors, farmers in Mymensingh and Rangpur are largely dependent on agriculture. Of these regions, Mymensingh is one of the regions with the highest poverty rates. The income share in income sources revealed that income category shares across the various regions of Bangladesh are far from uniform. Income share comparisons and cluster analysis classified the regions into three groups as follows. (1) In some regions, namely Rajshahi, Khulna and Dhaka, income from agriculture is important and these regions receive relatively high income. (2) In other regions, namely Mymensingh, Rangpur and Barisal, agriculture income is important but the regions receive relatively low income. (3) The other regions, which are Comilla, Chittagong and Sylhet, are not strongly dependent on agriculture and Comilla region strongly relies on income from remittances. The principal targets of agricultural research for poverty reduction are considered to be in group (2).

Variance decomposition of income showed that agricultural income in Mymensingh and Rangpur is the main cause of income differences. Moreover, large variances in agricultural income in the regions are induced by gross incomes from rice production, indicating that rice yield can have large impacts on income levels. Therefore, research and development and technical support for farmers to realize high and stable rice yields in these regions are important.

This paper used modelling to predict crop yield changes by different aspects of climate change under droughts, floods, flash floods, sea level rise and RCP scenarios. We account for some uncertainty in crop yields and the resulting reduction in per-capita income of farm households. The proposed lognormal distribution projected the poverty rate and examined the vulnerable regions. The key is to understand the future projections of poverty rates on assumptions of *boro* HYV and *aman* HYV rice yield decreases on each farm due the climate change impacts and climate volatility subjecting the poor to poverty rate increases in different regions. Current climate change impacts are not the same in different regions; in particular, different extreme climatic events in specific regions often result in irreversible losses. One of the examples of the interventions of climatic events is that dependency on agriculture with high variability in annual rainfall has render the northwestern parts highly vulnerable to droughts and has increased the high poverty rates, compared to other parts of the country. Extreme floods can increase the poverty rates in Rangpur, Mymensingh and Khulna regions. Kishorganj district is the most vulnerable on poverty (8.8% increase) if sudden flash floods occur in the northeastern part of the country. Due to sea level rise, coastal areas will face poverty.

Strategies and techniques to cope with climate change for regions where small-scale farmers are largely dependent on agriculture are important challenges. Among the negative consequences of climate change impacts, subsistence farmers are suffering more from vulnerabilities such as extreme poverty or hunger. However, adaptation techniques in agriculture are a vital tool to avoid the adverse impacts of climate change [117]. Given the complex nature of droughts, floods, flash floods and sea level rise as phenomena, the development of drought-tolerant, short-maturing and salt-tolerant varieties is critically important.

More generally, our results are focused on farm income and poverty, including regional vulnerability due to climate change impacts on agricultural production. In recent years, climate change impacts have played a vital role in increasing the poverty rate and income variability among farm households in Bangladesh. Extreme environmental hazards are faced by farmers in this country and their net farm production decreases drastically, increasing the poverty rate while changes in weather conditions are a less severe problem for farmers due to their involvement in other income activities. We actually performed this study focusing on revealing the comprehensive impact of climate change on farm production and the crops are that the most important for per capita income differences across the country and that enhance the poverty rate, using the covariance and lognormal distribution methods.

This study has attempted to bridge the gap between academic research and professional practices in the context of potential climate change impacts on crop production and poverty. Because of the relatively large sample size, compilation and manipulation of the data were challenging. With the assessment of poverty and regional vulnerability due to climate changes, it is hoped that the study in general will assist in guiding authorities in terms of interventions aimed at climate change risk reduction in Bangladesh. Therefore, we believe that this research will help to reveal the mechanisms behind the per capita income differences and projected poverty rates of farm households based on different climate change impact scenarios across Bangladesh. Future work might also be more micro level for policy making to test root-level poverty and to further evaluate the impact of climate change on different crops and it should include the model for poverty determinants to confirm the relationships studied and their adaptations.

Author Contributions: M.S.A. conceived the research, compilation and analyze the data, drafted, edited and revised the manuscript; J.F. modified the methodology of the research, checked, edited and revised the manuscript; S.K. designed, compilation and analyze the data, edited and revised the manuscript; M.R.B. checked the statistical tools and maps of the objective regions; and M.A.S. helps to compilation of data and first draft of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A.1

In this study, we used the primary data from Bangladesh Integrated Household Survey (BIHS 2011–2012) by IFPRI, https://dataverse.harvard.edu/dataset.xhtml?persistentId=hdl:1902.1/21266.

Appendix A.2

"*aus*" is former rainy season, "*aman*" is rainy season and "*boro*" is dry season irrigated rice.

Appendix B

Appendix B.1

$$\begin{aligned} Net\ accounting\ cost_i = & \sum_i \sum_j P_{ij} X_{ij} \\ & = c_{i,\ Rental\ cost\ of\ land} + c_{i,\ seed\ cost} + c_{i,\ irrigation\ cost} \\ & + c_{i,\ manure\ or\ compost\ cost} + c_{i,\ pesticides\ cost} + c_{i,\ fertilizer\ cost} \\ & + c_{i,\ draft\ animal\ cost} + c_{i,\ machinery\ cost} + c_{i, threshing\ cost} + c_{i,\ hired\ labor\ cost} \end{aligned} \tag{A1}$$

$$Production\ value_i = \sum_i P_i Y_i \tag{A2}$$

$$\begin{aligned} Gross\ income_i & = \sum_i P_i Y_i - Inkind\ payment_i \\ & = \sum_i P_i Y_i - (C_{i,\ irrigation\ cost\ paid\ by\ crop} + C_{i,\ labor\ cost\ paid\ by\ crop}) \end{aligned} \tag{A3}$$

$$Net\ income(\pi)_i = Gross\ income_i - Net\ accounting\ cost_i \tag{A4}$$

Appendix B.2

We estimate per-capita incomes (US$) of all sample families on assumption of climate change impacts and draw the distribution of the estimated incomes assuming that the distribution follows log normal distribution. To draw log normal distribution, we have to find mean and standard deviation of $ln(x)$. Firstly, we divide the per capita income in different class and make the average (x) of each class and we find the frequency of household (n) in each per-capita income class. Then we find the log of average per-capita class, log (x); and multiplied by the frequency of household in each class, n * log (x). Next average,

$$u = \frac{\sum n\{\log(x)\}}{\sum n} \tag{A5}$$

Then we estimate, $\log(x) - u$, $\{\log(x) - u\}^2$ and $n\{\log(x) - \mu\}^2$

Next standard deviation,

$$\sigma = \sqrt{\frac{\sum n\ \{\log(x) - u\}^2}{\sum n}} \tag{A6}$$

Returns the lognormal distribution of x, where ln (x) is normally distributed with parameters Mean and Standard deviation. Use this function to analyze data that has been logarithmically transformed.

$$\begin{aligned} f_X(x) &= \frac{1}{dx}Pr(X \leq x) = \frac{1}{dx}Pr(lnX \leq lnx) = \frac{1}{dx}\Phi\left(\frac{lnx-\mu}{\sigma}\right) = \varphi\left(\frac{lnx-\mu}{\sigma}\right)\frac{1}{dx}\left(\frac{lnx-\mu}{\sigma}\right) \\ &= \varphi\left(\frac{lnx-\mu}{\sigma}\right)\frac{1}{\sigma x} = \frac{1}{x}\cdot\frac{1}{\sigma\sqrt{2\pi}}exp\left(-\frac{(lnx-\mu)^2}{2\sigma^2}\right) \end{aligned} \tag{A7}$$

Syntax: LOGNORM.DIST(x, mean, standard deviation and cumulative)

Appendix C

Table A1. Household income (US$/yr.) from different sources, by region.

	B	CH	CO	D	K	M	RJ	RN	S	BD
Agril. crops	159.35	124.17	82.83	194.67	273.63	225.23	322.78	246.71	131.77	200.28
Main crops	76.23	44.11	35.22	118.52	152.25	127.87	202.10	170.95	89.86	116.89
Other crops	83.13	80.06	47.61	76.16	121.39	97.36	120.69	75.76	41.92	83.39
Fish	115.70	23.47	8.54	31.34	111.73	67.72	49.43	13.14	46.17	55.45
Livestock	27.43	17.81	22.35	51.76	86.61	57.25	76.48	35.67	26.20	48.60
Non-Ag. profit	260.29	293.63	212.95	304.83	254.71	197.39	338.22	171.49	292.70	262.92
Remittance	138.41	381.12	624.89	225.28	107.64	101.84	77.30	87.37	259.51	212.90
Employment	487.70	676.42	464.06	590.46	542.42	436.33	669.77	582.29	642.59	560.94
Other income	64.65	8.41	90.96	38.22	31.36	32.01	190.70	15.53	60.98	57.61
Total	1253.53	1525.04	1506.60	1436.53	1408.12	1117.77	1724.70	1152.23	1459.92	1398.71

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet, BD = Bangladesh, Main crops = *Aus*, *Aman* and *Boro* rice and other crops = Wheat, Maize, Jute, Potato, Chili, Onion etc.

Table A2. Each agricultural crop's share in total net agricultural income (%), by region.

Crops	B	CH	CO	D	K	M	RJ	RN	S	BD
Rice	45.51	33.66	32.99	37.39	43.52	55.62	51.27	57.72	67.05	47.22
Aus	6.37	2.89	1.51	0.64	3.03	0.84	1.11	1.39	5.19	2.24
Aman	24.36	17.83	6.42	5.22	15.55	15.37	17.27	22.12	18.45	14.96
Boro	14.78	12.95	25.06	31.54	24.95	39.42	32.89	34.21	43.41	30.02
Wheat	0.00	0.00	0.19	0.22	0.70	0.07	1.32	0.96	0.00	0.48
Maize	0.00	0.00	0.84	0.30	0.26	0.00	1.40	2.01	0.00	0.56
Jute	0.61	0.00	3.03	10.53	5.85	0.44	2.80	2.96	0.11	4.37
Potato	0.66	0.37	5.49	0.53	0.18	0.36	4.04	4.68	1.00	1.62
Chili	1.82	2.17	2.69	6.85	5.72	1.54	0.67	1.20	0.53	3.40
Onion	0.00	0.00	0.01	5.79	1.01	0.00	1.81	0.32	0.00	1.70
Other crops	51.39	63.80	54.77	38.38	42.76	41.96	36.67	30.16	31.31	40.65
Total	100	100	100	100	100	100	100	100	100	100

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh.

Table A3. Costs and income (US$/ha) associated with aman and boro HYV rice production, by region.

	Aman HYV										*Boro* HYV									
	B	**CH**	**CO**	**D**	**K**	**M**	**RJ**	**RN**	**S**	**BD**	**B**	**CH**	**CO**	**D**	**K**	**M**	**RJ**	**RN**	**S**	**BD**
b	53.77	74.83	76.13	53.84	30.12	45.34	46.93	38.08	57.28	47.08	64.59	82.41	75.69	50.94	32.39	45.13	49.55	42.71	54.49	49.14
c	64.29	38.14	72.11	79.90	64.27	33.96	45.27	30.77	45.13	47.80	60.51	46.47	70.82	71.22	66.36	42.49	73.53	40.41	43.01	58.24
d	1.33	4.58	8.04	34.37	11.12	27.00	37.48	12.43	5.65	19.52	63.70	60.16	135.28	165.63	114.87	122.83	116.16	93.95	61.48	113.42
e	1.19	1.54	2.87	1.55	1.73	2.81	7.00	2.45	3.84	3.22	2.40	5.36	9.24	4.22	10.59	8.17	8.65	25.41	1.92	7.98
f	5.98	11.33	8.48	6.22	3.34	9.16	9.36	9.31	4.81	7.49	14.01	14.25	13.96	7.34	9.24	13.41	11.12	13.73	3.65	9.72
g	26.33	45.58	60.39	50.65	40.65	63.05	49.46	50.75	27.61	47.88	59.67	92.28	92.46	90.84	97.05	106.66	73.24	107.18	45.80	84.34
h	9.08	0.61	0.43	0.67	2.57	3.96	1.61	1.84	6.60	3.22	1.55	1.58	0.30	1.02	2.82	5.72	2.55	2.06	5.54	3.05
i	26.59	43.06	37.71	33.86	25.06	25.65	22.36	26.46	31.04	27.43	42.48	46.83	36.75	33.65	28.94	26.73	21.83	30.41	25.77	29.51
j	17.58	17.31	9.34	6.11	9.51	8.45	4.04	3.36	5.89	7.64	15.92	29.29	14.55	16.23	19.54	10.05	5.96	9.59	4.27	11.99
k	85.80	155.19	133.77	171.81	113.27	115.80	134.27	106.25	107.67	120.55	152.40	305.40	237.84	242.40	151.19	157.81	190.60	125.47	227.20	192.16
TC	291.93	392.18	409.27	438.98	301.63	335.18	357.78	281.70	295.53	331.82	477.24	684.02	686.89	683.49	533.00	539.01	553.19	490.92	473.14	559.55
TP kg/ha	3573	3655	1913	3131	2515	2776	3650	3500	2572	3023	4659	4821	5136	6181	5122	4950	6025	5733	4218	5304
GI	734.65	710.58	387.39	614.66	477.69	577.30	661.75	669.42	476.78	585.58	841.58	964.00	999.64	1169.99	1009.64	1082.65	1115.88	1115.55	749.11	1023.34
GI-TC	442.72	318.40	−21.88	175.69	176.07	242.12	303.96	387.72	181.25	253.75	364.35	279.98	312.75	486.49	476.65	543.65	562.69	624.64	275.96	463.80

B = Barisal, CH = Chittagong, CO = Comilla, D = Dhaka, K = Khulna, M = Mymensingh, RJ = Rajshahi, RN = Rangpur, S = Sylhet and BD = Bangladesh; b = Rental cost of land, c = Seed cost, d = Irrigation cost, e = Manure/compost cost, f = Pesticide cost, g = Chemical fertilizer cost, h = Draft animal cost for land preparation, i = Rental cost for tools and machinery, j = Threshing cost, k = Hired labor cost, TC = Total cost, TP = Total production and GI = Gross income.

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