Article

Impact of Climate Change on Cotton Production in Bangladesh

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Abstract: Bangladesh produces only 5% of the cotton she needs to sustain her ready-made garments industries. The country has very limited agricultural land and cotton competes with other crops for this scarce land resource. On top of that, Bangladesh is regarded as a country where agriculture is highly vulnerable to the variabilities of weather patterns that result from climate change. Against this backdrop, to better understand the potential for the sustainable expansion of cotton production in Bangladesh, we examine cotton’s agricultural value chain and projected climate risks associated with different phases of the chain. We identified associated stakeholders at different phases of cotton production, engaged with them to understand climatic and non-climatic threats and developed an integrated set of recommendations for climate-risk management through improving the connection of producers to markets, increasing economic returns to small farmers, and improving efficiency along the value chain. We discussed our estimated climate projections with stakeholders to understand the challenges at different stages of production and marketing, and together explored and identified probable solutions. This research offers a new and evolving approach to assess climate change impact on agriculture utilizing a holistic approach, which could be adopted for other crops.

Keywords: climate change; agriculture; value chain approach; multi-criteria analysis; Bangladesh; cotton

1. Introduction

Global climate change has already had observable impacts across the world through rising temperatures, variability in rainfall, shifts in seasons, increasing salinity in coastal areas, and the increased frequency and intensity of extreme weather events. South Asia, with almost 25% of the world’s population, is exceptionally vulnerable to the effects of climate change because half of the region’s population is dependent on agriculture as their primary source of livelihood [1]. Bangladesh is already facing the impacts of climate change, making it an immediate concern in the country. The country’s topography and geographical location make it susceptible to extreme weather events including cyclones, floods, and storm surges, and its economy relies heavily on agriculture, which is highly climate sensitive [2]. Projections based on different scenarios of the Intergovernmental Panel on Climate Change (IPCC) special reports indicate that warming will accelerate over this century and project Bangladesh’s mean annual temperature will increase by between 0.9 and 2.6 °C by the 2060s and between 1.3 and 4.1 °C by the 2090s [3]. Many parts of Bangladesh are likely to experience a decline in crop productivity unless there is a shift to
different crop varieties and management practices. Any decline will not only adversely affect the livelihoods of those dependent on agriculture but also threaten food security, especially for vulnerable and marginalized sections of the population [2]. As a result, shifts to more climate resilient crops are imperative to secure the viability of agriculture-based livelihoods.

Cotton has certain features, such as a deep, vertical taproot, that make it more resilient to high temperatures and salinity [4]. It requires less water than paddies and thus can grow more easily in the highlands [5]. Bangladesh is the world’s second-largest exporter of ready-made garments (RMG) [6]. Bangladesh has set a target to grow its RMG sector by a 10.9% raise annually to reach the $50 billion RMG export target by 2021 [7]. The country’s current cotton production is sufficient to meet barely 5% of this demand and Bangladesh currently imports 4–4.2 million bales of raw cotton every year [8]. Sustainable initiatives that ensure good production practices along with effective management of cotton’s various value chain activities, can expand cotton production to bridge this gap. About 500,000 hectares of land are suitable for cotton production in Bangladesh [8]. This includes land in the highlands, drought-prone areas, and coastal regions that currently remain fallow or is not viable for paddy cultivation [9].

In response to the decline in the country’s major crop’s productivity due to climate change, the agriculture sector is seeing an increase in crop diversification [10]. Cotton cultivation could play an important role in this shift in cropping patterns. To fully understand the potential for promoting cotton as a suitable climate-resilient crop, it is necessary to first understand the effects of climate change on cotton production. Unfortunately, there is insufficient research on climate change impacts to Bangladesh’s agriculture in general and no research on its impacts on cotton cultivation in Bangladesh.

This research strives to understand the impact of climate change on cotton production by examining the different activities along its full value chain. It provides a foundation for studying climate change impacts on cotton in Bangladesh, as well as outlining a general methodology that can be used to study the climate resilience of other crops.

This research aligns with growing global interests in identifying sustainable and adaptive agricultural practices in the face of a changing climate. However, instead of focusing only the climatic risks, this paper proposes a more comprehensive understanding of the entire crop value chain to reduce the vulnerability of all players involved. This approach widens the lens for examining climate change impacts on agriculture and brings a new perspective to the discourse.

2. Value Chain Approach to Enabling Agricultural Climate Change Adaptation

A “value chain” in agriculture describes the range of activities and set of actors that bring an agricultural product from production in the field to final consumption. At each stage, value is added to the product (shown in Figure 1). A successful agricultural value chain is both productive and sustainable [11]. The various processes and stages along the value chain work together to conserve the environment and natural resource base; adapt to climate change; respond to price fluctuations and consumer needs; and provide sustainable pathways to sufficient, nutritious, and affordable food or other agriculture-based products [12]. This study looked specifically at the cotton value chain to identify factors that make it relatively resistant to climate impacts and identified existing bottlenecks across the value chain that reduce the viability or profitability of the product and hence hinder the expansion of its cultivation.

In agriculture, climate risks are considered as business risks. Here, climate hazards, such as droughts, floods, and changing rainfall patterns do not only occur on the farm itself, rather affect all actors along the entire value chain in different ways and to different extents [13]. Most actors make efforts to reduce these negative impacts, but not all responses are affordable and/or sustainable. A value chain approach is an integrated climate risk management approach that acts not just to build climate resilience but also to provide more effective support to agriculture [14]. It recognizes the interdependence of actors involved in
all stages of a value chain, from production to consumption, and guards against economic and climate change risks that threaten any part of this chain [15]. Thus, using the value chain approach as an analytical tool can play a significant role in building climate resilience.

| Pre-production | Production | Processing | Marketing | Consumption |
|----------------|------------|------------|-----------|-------------|
| +Value         | +Value     | +Value     | +Value    | +Value      |

- Reduced seed quality (poor germination)
- Reduced yield
- Crop failure
- Poor vegetative growth/stunting/rotting
- Excess labour needed for weeding, harvesting, drying
- Reduced quantities available for agro-processing
- Poor quality harvested crop leads to the poor quality processed product
- High moisture content – lower prices for farmers, and higher losses in processing
- Delayed delivery/distribution
- Congestion or damage to transportation routes
- Delayed distribution
- Reduced food availability
- Price volatility
- Higher price

Figure 1. Potential climate change impacts on an agricultural value chain (Source: Adapted from [14]: p. 4).

To be resilient to the impacts of climate change impacts, farming systems have to adapt to new rainfall or temperature regimes, as well as survive recurrent extreme events. In Bangladesh, shifts in the monsoon timing have an impact on both yields and crop choices [16]. In most cases, responding to changes in weather patterns requires adjustment to cropping patterns to build more resilience into the farming system. However, to do this effectively, it requires shifts in the composition of cropping patterns to include more climate-resilient crops and/or varieties [17]. In this context, diversification becomes an
important risk mitigation tactic for farmers. However, diversification is only likely to be effective and successful if farmers can make informed choices on diversification options. Farmers, especially poorer ones, may not have access to adequate information to identify crops that are likely to thrive in the changed climatic conditions. Even if they know of potentially climate-resilient crops, they may not have the knowledge and experience to cultivate them successfully or know whether suitable markets exist [13], and what happens on the farm is not the whole story. Climate change can have impacts along the whole value chain and the most constraining bottlenecks along the chain may not be the farm production process itself [14].

Considering all these, this research describes a “Value Chain Approach” that provides a generic methodology that can be used to understand constraints and opportunities in developing markets for any crop. However, it is important to note that although it follows the whole value chain, it is slightly different from its conventional application as an economic tool, which sets out to identify how value is added at each stage along a commodity’s value chain. Instead, this study used this approach to explicitly explore existing vulnerabilities, which will exacerbate the impacts of climate change on the entire value chain. It considers impacts that range from access to land and the effectiveness of input supplies, through farm production and postharvest storage and processing, on to the journey to market and the final consumer [18]. It explores the detail of each of these various stages and the stakeholders involved at each stage (please see [14] for detailed methodology).

3. Materials and Methods

In an ideal situation, a “Climate Resilient Value Chain Approach” involves five steps as listed below and shown in Figure 2.

- Selecting a climate-vulnerable study area.
- Selecting the climate-vulnerable crop.
- Identity the actors.
- Identification of climate risks and impacts on selected crop through its value chain.
- Presenting findings and agreeing on the next steps with the key stakeholders.

3.1. Selection of Crop and Study Area

Multi-Criteria Analysis (MCA) is used for steps a and b, and a form of value chain analysis for steps c and d. Step e is managed through consultative feedback, using validation workshops to present results, recommendations and agreeing on the next steps with the main governing body responsible for that crop. However, in this study, we did not conduct a multi-criteria analysis as cotton was a pre-selected crop based on the interest of the Bangladesh Cotton Development Board (CDB). Here, in response to the CDB’s request,
we followed an approach where both the crop and study areas were selected based on expert opinions and the interest of the client.

The Bangladesh Cotton Development Board hosted and supported designing this research. Based on their expert opinions, two climate hotspots—the High Barind Tract and the High Ganges Floodplain—were selected. The research sites are in the northwest and southwest parts of the country respectively under two different agro-ecological zones. The Barind Tract’s climate is warm and humid. This region is relatively drier than many parts of Bangladesh and Rainfall mainly occurs during the monsoon season [19]. The area is also experiencing water scarcity in its topsoil during the dry season. Therefore, this region is designated as a drought-prone area. On the other hand, the Ganges River Floodplain climate is cooler and considerably wetter than the High Barind Tract zone. [20]. This zone is regarded as a flood-prone area of Bangladesh. Hence, the CDB experts suggested these two areas as climate hotspots. Guided by CDB’s expert opinion, we selected three districts in the High Barind tract region—Rajshahi, Naogaon, and Chapai Nawabganj and two districts, Meherpur and Kushtia, from the High Ganges Floodplain.

3.2. Data Collection

The CDB, who are already providing a field-level support service to the cotton farmers, facilitated and supported the research team. They helped us to understand the cotton value chain and guided us in the initial identification of stakeholders at different levels. CDB’s scientists and field managers supported us to design the research process and adapt our analytical tools to suit the local context. Following our introduction to the cotton value chain in Bangladesh, we divided the field research into two phases over six months. The first phase took place during the pre-plantation period when the farmers prepare their lands, collect seeds, fertilizers, and pesticides, and organize irrigation arrangements. We used the first fieldwork to orient ourselves to the field and the farmers, updating our knowledge of the cotton value chain, identifying the stakeholders and their line of engagements, piloting and upgrading designed research tools and running a small survey with the farmers, reflecting on their experience of cotton production last year. Six months later, we ran the second round of fieldwork. By then we had the results of our first round of fieldwork ready to assist us with further investigation. It was a pre-harvest period when the cotton crop has produced green cotton balls ready to crack open in a few weeks. At that stage of the cultivation cycle, farmers have some time to pause and reflect on their past actions to shape their future decisions. That was an ideal time to go back to the cotton farmers and connect to the other stakeholders to analyze the issues strategically that had surfaced during the first phase. In parallel, we collected meteorological data from the Bangladesh Meteorological Department (BMD) to understand changes in weather system patterns. This data helped us corroborate farmers’ perception of shifts in weather patterns over the past decade, as noted during interviews with cotton farmers and other stakeholders.

3.2.1. Climatic Data and Model

Data from Rajshahi and Chuadanga BMD stations were used to analyze the climatic condition of the High Barind Tract zone and High Ganges Floodplain, respectively. As there are variations in rainfall data at a micro-scale, the study only used satellite data, which is available for the past 20 years (1998–2017) to develop local-level climatic patterns. It used precipitation and temperature data from BMD weather stations and grid wise-satellite data from the Tropical Rainfall Measurement Mission (TRMM) and the Precipitation Estimation from Remotely Sensed Information Using Artificial Neural Networks (PERSIANN) system. Chuadanga and Rajshahi have been analyzed using BMD data. As there are no BMD stations in Nachol and Porsha Upazilas (in Chapai Nawabganj and Naogaon districts, respectively, of the High Barind Tract) the research used National Aeronautics and Space Administration (NASA) Satellite TRMM_3B42_daily data. TRMM data are better correlated than PERSIANN data with observed BMD data for Rajshahi and Chuadanga weather stations. The past decade’s rainfall patterns across the region were also analyzed to
understand shifts and variability over time and identify the implications of these for agriculture in the region. Standard statistical tools (i.e., averages, percentages, Linear Trend Model (LT), Quadratic Trend Model (QT), and graphical presentations) were used for analysis, interpretation, and to infer conclusions to answer the assessment objectives.

3.2.2. Qualitative Data Sources and Techniques

The fieldwork strove to understand the dynamics of cotton cultivation as experienced by farmers, input dealers, processors, and to identify challenges, contradictions, and opportunities across the crop’s value chain. At the very outset, we conducted focus group discussions to develop insights into existing challenges, significant themes, and local practicalities. We conducted four focus group discussions in different locations with approximately 12–15 farmers in each group. Following standard research protocol, we recorded, translated, coded, and analyzed our discussions. These focus groups were both in the open and in close spaces with an open entry and exit to allow farmers to be accommodated comfortably. These focus groups were vital to revise and update our knowledge of the cotton production process and situate ourselves in the local settings. Across the study area, we interviewed 60 cotton farmers (20 in the pre-plantation and 40 in the pre-harvest periods) using a field-tested questionnaire which captured detailed information covering activities from seedbed preparation to consumption, for all the crops they grow. This exercise made it possible to combine data on cotton production with data on other crops, which could then be analyzed to unpack the strengths, weaknesses, opportunities, and threats at different points along the value chain. We identified and interviewed local stakeholders, such as input seed companies, moneylenders and other financial institutions, dealers, traders, wholesalers, and processors for different crops of the cotton cropping system through formal and informal interactions with the local farmers. Interviews with stakeholders were useful to understand their perceptions and experiences in those parts of the cotton value chain that each was involved in. This information built a clearer picture of a complex value chain.

3.3. Data Manipulation and Analysis

From the very early stage of research design to the final report submission, scientists from the CDB were involved in this research. For example, the research team presented the research design, initial findings, and final recommendations to the CDB colleagues to obtain their feedback and ensure the research was relevant to their future operational plan. This meant that, in addition to an extensive literature review, field-based assessment, and meteorological data, the research was also informed by the suggestions and perceptions shared by various relevant stakeholders. The research team undertook the field research and interacted with different stakeholders as learners, treating informants as mentors. Information was carefully documented, and all data cross-checked with informants to try to ensure the emerging storyline was not influenced by the researchers’ values and bias.

4. Results

4.1. Changing Pattern of Monthly Average Rainfall and Temperature

The High Barind Tract area lies in the summer monsoon region of the northern hemisphere. The tropic of cancer lies south of this region, which makes the climate of the area warm and humid. Rainfall is comparatively low in this region and mainly occurs during the monsoon season. The highest daily rainfall recorded is 247 mm [19]. In Bangladeshi standards, this region is often designated as a drought-prone area. Its average temperature ranges from 25 to 35 °C in the hottest season and 9 to 15 °C in the coolest season. In summer, some of the hottest days experience maximum temperatures of about 45 °C or more, while in winter it falls to around 5 °C [21]. So, this region experiences extremes that are in clear contrast to the climatic condition of the rest of the country. The monthly normal minimum temperature, maximum temperature, and rainfall of this area during 1981–2010 are shown in Figure 3.
summer, some of the hottest days experience maximum temperatures of about 45 °C or more, while in winter it falls to around 5 °C [21]. So, this region experiences extremes that are in clear contrast to the climatic condition of the rest of the country. The monthly normal minimum temperature, maximum temperature, and rainfall of this area during 1981–2010 are shown in Figure 3.

Temperature data recorded at Rajshahi weather station shows that the maximum temperature of this region is increasing over time by 0.068 °C/decade, whereas the minimum temperature is decreasing at a rate of 0.008 °C/decade. Figure 4 shows the temperature trends in this area for the period 1971 to 2010.

The prominent features of wind climatology in Bangladesh are the circulations influenced by the strong southwest monsoon when warm and humid air moves towards the land. The distribution of wind direction and wind speed of High Barind Tract area during different seasons, recorded using the Windrose (using R software) of the BMD’s weather stations at Rajshahi and Khulna, shows that winter weather comes from a predominantly northerly direction. In the monsoon, the winds are predominantly westerlies in the High Barind Tract and southerly in the High Ganges River Floodplain. These strong cold winds in the study areas reduce the yield of cotton due to boll shedding.
The upper Ganges floodplain receives more rainfall and is cooler, with fewer temperature extremes than the High Barind tract. The highest 24 h rainfall of this area was 430 mm, which is almost double the High Barind Tract. During the period 1948–2013, the lowest minimum and highest maximum recorded temperatures in this region were 6.4 °C and 43.5 °C, respectively [20]. The monthly mean minimum and maximum temperatures, and rainfall are shown in Figure 5.

Figure 5. Monthly mean minimum and maximum temperature and rainfall duration of the high Ganges river floodplain area during 1981–2010.

The temperature data recorded at Khulna weather station shows that the maximum temperature of the high Ganges river floodplain region is increasing over time by 0.06 °C/decade, whereas the minimum temperature is decreasing at a rate of 0.021 °C/decade. Figure 6 shows the temperature trends of this region for the years 1971 to 2010.

Figure 6. Mean temperature trend over High Ganges Floodplain.

4.2. Rainfall Pattern in Different Cropping Phases

One of the objectives of this study is to identify the major climatic risks of cotton production in Bangladesh. The climatic analysis focused on three major phases of cotton production (Table 1):
1. Plantation Season (July–August),
2. Flowering Season (October and November), and
3. Harvesting Season (December–March).

Table 1. Rainfall (in mm) in the study sites classified at different stages of cotton farming.

| Seasons                  | Regions         |
|--------------------------|-----------------|
|                          | Kushtia | Rajshahi | Nachol | Porsha |
| Plantation (July–August) | average 518.4  | 489.3    | 567.6  | 583.2  |
| Flowering (October–November) average | 160.8  | 130.7    | 144.5  | 176.4  |
| Harvesting (December–March) average | 63.2    | 45.6     | 38.6   | 36.6   |

Source: BMD (2018). http://live3.bmd.gov.bd/.

These three phases are further extended into six different stages of the cotton plant growth, as shown in Table 2, which also shows the water requirements for the different growth stages. The water requirements follow a normal distribution curve, with minimum water needs at the beginning and end, and peak demand during the middle (flowering) stage, from the middle of September to the middle of November. Any delay in planting results in a delayed middle stage, which means the rainfall season would have ended and the cost of irrigation would increase. Delayed sowing can also be a result of adverse environmental conditions. For example, excessive rain between mid-July and August can lead to delayed plantations. For satisfactory plant emergence, adequate soil moisture is a necessity—however, seeds rot in very wet conditions.

Table 2. Cotton water requirements.

| Growth Stage                  | Water Use (mm per Day) | Days after Sowing | Duration of Growth Stage (Days) | Water Requirement (mm) |
|-------------------------------|------------------------|-------------------|--------------------------------|------------------------|
| Planting to emergence         | Low                    | 0–7               | 7                              | Moist land, no rainfall required |
| Emergence to 1st square       | 3                      | 7–30              | 23                             | 69                     |
| 1st square to 1st flower      | 6                      | 30–55             | 25                             | 150                    |
| 1st flower to peak bloom      | 9                      | 55–110            | 55                             | 495                    |
| Peak bloom to open bolls      | 6                      | 110–130           | 20                             | 120                    |
| Open bolls to harvest         | 1                      | 130–175           | 45                             | 45                     |

Source: CDB Desk Data (2018). http://www.cdb.gov.bd/.

As depicted in Table 3, the average rainfall trends in different study areas are decreasing at a rate of 0.012, 0.20, 0.088, and 0.18 mm/year, respectively. In the post-monsoon season, it is decreasing by 0.053 mm in the 10th year and 0.054 mm in the 20th year. In winter, the average rainfall is increasing by 0.01 mm/year. The volume of rainfall during the cotton planting period is dropping in all the study areas. Our study reveals that rainfall is increasing during the harvesting period only in Rajshahi. It is steadily decreasing by 0.36 mm/year in the monsoon and increasing by 0.007 mm/year in winter in Rajshahi. In Nachol, annual rainfall is decreasing by 0.088 mm/year. The post-monsoon rainfall decrease is 0.14 mm/year. In winter, rainfall is increasing by 0.006 mm/year. In Porsha, the average rainfall is decreasing by 0.18 mm/year. In the post-monsoon season, rainfall is decreasing by 0.26 mm/year and in winter it is decreasing by 0.006 mm/year.

This study also analyzed dry spells in the monsoon (plantation) and wet spells in winter (harvesting). Periods of more than four days without precipitation during the monsoon are classified as dry spells, and periods of one or more days of precipitation in winter are classified as wet spells. These are shown in Figures 7 and 8, where the dotted line indicates their trend. These are generally decreasing in July and increasing in August. If
this trend continues, it will be difficult for farmers to find a sowing phase in July, when they need moist land with no rainfall. Thus, sowing will likely move to August, when dry spells are increasing. However, wet spells in winter are decreasing, which favors harvesting.

Table 3. Average rainfall trends in different study areas classified according to different seasons.

| Region   | Overall Fitted Model | Projected Rainfall Changes | Comment on the Seasonal Growth Rate |
|----------|----------------------|-----------------------------|-------------------------------------|
| Kushtia  | LT                   | 0.01                        | D                                   |
|          |                      |                             | I                                   |
|          |                      |                             | D                                   |
|          |                      |                             | I                                   |
|          |                      |                             | D                                   |
|          |                      |                             |                                      |
| Rajshahi | QT                   | 0.20                        | D                                   |
|          |                      |                             | I                                   |
|          |                      |                             | D                                   |
|          |                      |                             | D                                   |
|          |                      |                             | I                                   |
|          |                      |                             | I                                   |
| Nachol   | LT                   | 0.09                        | D                                   |
|          |                      |                             | D                                   |
|          |                      |                             | D                                   |
|          |                      |                             | I                                   |
|          |                      |                             | D                                   |
| Porsha   | QT                   | 0.18                        | D                                   |
|          |                      |                             | D                                   |
|          |                      |                             | D                                   |
|          |                      |                             | D                                   |

(Note: LT = Linear Trend Model; QT = Quadratic Trend Model; I = Increasing; D = Decreasing).

![Figure 7](image1.png)

Figure 7. The trend of four or more consecutive dry days in monsoon season and one or more wet days spells in winter season at High Barind Tract.

![Figure 8](image2.png)

Figure 8. The trend of four or more consecutive dry days in monsoon season and one or more wet days spells in winter season at High Ganges River Floodplain.

4.3. Seasonal Temperature Variabilities

While analyzing temperature, maximum (daytime) and minimum (night) temperature was considered, and the mean temperature is the average of the maximum and minimum temperature. In this study, only the linear trend model (LT) is used, because the LT, quadratic trend model (QT) and growth curve model results are almost identical.

Tables 4 and 5 show that the maximum temperature in the High Ganges Floodplain is increasing at 0.011 °C/year or 1.1 °C/100 years. The minimum temperature is decreasing...
at 0.015 °C/year or 1.5 °C/100 years. In the post-monsoon season, the mean temperature is decreasing at 0.07 °C/year or 7.0 °C/100 years. In winter, the decrease rate is 0.035 °C/year or 3.5 °C/100 years.

Table 4. Temperature requirement for different stages of cotton production (°C).

| Regions                      | Seasons                               | Maximum | Minimum | Mean |
|------------------------------|---------------------------------------|---------|---------|------|
| High Ganges Floodplain       | Plantation (June–September) average  | 33.4    | 26.2    | 29.8 |
|                              | Flowering (October–November) average  | 31.1    | 20.6    | 25.8 |
|                              | Harvesting (December–March) average   | 28      | 14.1    | 21.1 |
| High Barind Tract            | Plantation (June–September) average  | 33.5    | 26.2    | 29.9 |
|                              | Flowering (October–November) average  | 30.7    | 20.5    | 25.6 |
|                              | Harvesting (December–March) average   | 27.6    | 13.9    | 20.7 |

Table 5. Rate of increase in temperature in the study areas.

| Region                      | Overall Fitted Model | Projected Temperature Changes | Comment on the Seasonal Growth Rate (°C/100 Years) |
|-----------------------------|----------------------|-------------------------------|-----------------------------------------------|
|                             |                      | Rate (°C/100 Years)           | Increase/Decrease over Historic Trend | Pre-Monsoon | Monsoon | Post Monsoon | Winter |
| High Ganges Floodplain      | LT                   | 1.1 (Max) 1.5 (Min)           | I     D                                      | 3.4 (Mean) I 1.1 (Mean) I 7 (Mean) D | 3.5 (Mean) I |
| High Barind Tract           | LT                   | 2.8 (Mean)                    | I     D                                      | 5.8 (Mean) I 4.6 (Mean) I 1.4 (Max) I 9.7 (Min) D | 0.2 (Mean) I |

(Note: LT = Linear Trend Model; QT = Quadratic Trend Model; I = Increasing; D = Decreasing).

The overall changing mean temperature rate for the High Barind Tract is increasing at 2.8 °C/100 years. However, in the High Ganges Floodplain, the maximum temperature is increasing, and the minimum temperature is decreasing, at 1.10 °C/100 years and 1.50 °C/100 years, respectively. Both maximum and minimum temperatures during the cotton plantation period are rising, and the rate of increase is higher in the High Barind Tract. Similarly, temperatures are rising during the cotton harvesting season (December–March) in all the study areas, though the rate of increase is higher in the High Ganges Floodplain.

Both maximum and minimum monsoon temperatures are increasing in the High Barind Tract. According to the projection, the increasing trend rate for the average temperature is 0.046 °C/year or 4.60 °C/100 years. The overall mean temperature is decreasing in the post-monsoon season and increase in the winter. In the post-monsoon season, the maximum temperature is increasing at 0.014 °C/year or 1.4 °C/100 years and the minimum temperature is decreasing at or 0.097 °C/year or 9.7 °C/100 years. In winter, the increasing rate is 0.002 °C/year or 0.2 °C/100 years.

5. Discussion

5.1. Impact of Climate Change on Cotton Cultivation

Due to having vertical taproots, cotton is to some extent resilient to high temperatures, drought, and salinity. Nevertheless, it is a climate-sensitive crop. Greenhouse gas emissions take place at different stages in the cotton value chain, although the amount is not significant [22]. Thus, it both contributes to climate change and is being affected by the impacts of climate change. However, the extent to and ways in which climate change affects cotton cultivation depend on the geographical location. Climate change will affect cotton cultivation through higher carbon dioxide (CO₂) levels, higher temperatures, lower humidity, and shortages in water availability [23]. Cotton is classified as a C3 plant due to the way it assimilates carbon dioxide through photosynthesis and, because of this, elevated CO₂ levels in the atmosphere can bring positive impacts [24]. By utilizing the higher CO₂ levels, the plants can produce larger leaves, meaning a larger surface area for
photosynthetic activities [25]. This, in turn, results in a greater number of branches, leaves, and bolls [26]. However, higher vegetative growth can increase the demand for irrigation, fertilizers, and pesticides. The increased concentration of CO$_2$ may increase the efficiency of water use, partially compensating for the stress caused by water scarcity [11].

There are both positive and negative effects of temperature rise on cotton farming. The temperature influences cotton growth and development. It determines the rate of node development, fruit production, photosynthesis, and respiration. A rise in the average daily temperatures may result in better growth of cotton. On the other hand, climate change may increase the number and severity of hot days during cotton’s growing season. Increased heat stress can damage plant tissue, resulting in parrot-beaked bolls, boll freeze, and cavitation, which reduces the yield [27]. Fiber lengths shorten and micronaire values (a measure of the air permeability of compressed cotton fibers) increase if the temperature is high during boll filling. The negative impacts of hot conditions on yield and quality are exacerbated if water stress occurs simultaneously.

The temperature requirement for the growth and development of cotton plants at different growth stages is presented in Table 6.

**Table 6. Temperature requirement for cotton growth and development.**

| Growth Stage                  | Days  | Cumulative Heat Units (Days Degree, DD16 = (°C Max + °C Min)/2 – 16) |
|-------------------------------|-------|---------------------------------------------------------------------|
| Planting to emergence         | 4–9   | 10                                                                  |
| Emergence to the first square  | 27–38 | 435                                                                 |
| Square to flower              | 20–25 | 735                                                                 |
| Planting to the first flower   | 60–70 | 1510                                                               |
| Flower to open boll           | 45–65 | 2360                                                               |
| Planting to harvest-ready     | 130–160 | 4560                                                             |

Source: CDB Desk Data (2018). http://www.cdb.gov.bd/.

Cotton has different water requirements at different stages of its growth. The young plants can tolerate relatively dry conditions and can continue to flower under water stress. However, once the flowers are out, the water requirement increases considerably. Water scarcity in the first 14 days after flowering may cause the cotton bolls to fall off [28]. A water deficit can stall both plant growth and the development of fiber length, which could lead to lower yields. The lower the fiber length, the poorer the quality, the cheaper the price and the smaller the cotton farmer’s income. The cotton crop is also very sensitive to temperature. A range of 20 °C to 40 °C of the daytime temperature is ideal for bud formation. As we see in Table 6, it takes about two months to progress from flowering to bud formation [29]. Strong and cold winds may crack open a matured bud before it is ready for harvest. This can also reduce the quality of the cotton fiber and its yields because dust gets trapped in it.

In a changing climate, an increase in rainfall intensity may become a problem for cotton farming. Although the water requirement during the flowering season is high, during harvesting the cotton fiber becomes highly sensitive to rain, which can cause flowers, buds, and bolls to fall and be damaged. Too much rain in the final stage of growth can also damage the quality and yield, since insect attacks, pests, and diseases can be more frequent at this point [31]. An increase in atmospheric CO$_2$ may also exacerbate the problem of pests and insect attacks. For example, the leaf-eating cotton caterpillar (*Spodoptera litura*) eats 30%
more leaves and lays more eggs under elevated CO$_2$ conditions [32]. Higher temperatures create favorable conditions for the survival and reproduction of cotton sap-sucking pests like whiteflies, thrips, aphids, mealybugs, and many others, which cause serious yield losses in cotton [27].

5.2. Climatic Risks across the Cotton Value Chain

This segment focuses predominantly on the risks across the value chain of cotton. In evaluating risk factors, this study took both climatic risks and value chain bottlenecks on the account.

Bangladesh is often labelled as “climate change ground zero” because of its susceptibility to extreme weather events. However, the slow onset of longer-term shifts in climate and weather patterns represent a less dramatic, but equally serious, threat to crop production in Bangladesh. Understanding the sustainability of cotton in this low-onset context is a primary concern of this research.

Rainfall variability: Rainfall data also shows that, in all our local study areas, rainfall patterns are changing, winters are becoming drier and monsoons are becoming gradually wetter. Rainfall variability could result in delays in sowing, loss of seeds, rising irrigation costs, favorable conditions for pests, fungi, and other microorganisms, production losses, poor quality harvests, loss of storage, and many other adverse impacts.

Increasing occurrence of drought conditions: Rainfall data shows that, overall, rainfall is decreasing in the post-monsoon season and winter, with dry spells also increasing in frequency, particularly in August and September. At the same time, agricultural intensification means farmers are extracting groundwater for irrigation. The water table is dropping, which is leading to scarcity when water is most needed—when cotton plants are flowering. The water situation is particularly challenging in Porsha, the driest part of the High Barind Tract. This is not only increasing irrigation costs but also adversely affecting cotton production.

Long cropping period: Cotton is a long-duration crop, with a planting to harvest readiness time of 130–160 days and its successful cultivation is also very much reliant on the temperature. Planting generally begins in the middle of July but can continue until the middle of August. Harvesting begins in December and continues until March. In this eight-month cropping period, cotton often becomes susceptible to changing climatic conditions. A shorter cropping period would be more resilient to variability in weather patterns.

Lack of information: Farmers do not have adequate information on weather variability and seasonal forecasts. For example, a warning of rain in July and August would help them make better decisions on sowing. Similarly, early information on winter rain would make them better prepared for harvesting and post-harvesting storage.

Increasing temperatures: Increased temperatures and moisture favor the growth of certain pests and fungi. During the second field visit, farmers in Kushtia pointed out attacks of fungi that spoil cotton bolls before they burst out. This is one of the unseen risks that farmers need to be prepared for. Pod sucking bug (Riptortus serripes), whitefly (Bemisia tabaci), mealybugs (Phenacoccus solenopsis), and red cotton bug (Dysdercus cingulatus) are common pests.

Lack of storage infrastructure and humidity: A delayed collection of harvested cotton, because there are a limited number of ginners with knock-on constraints on the availability of transport, combined with a lack of adequate farm-level storage, causes damage to post-harvest cotton. A relatively wet winter will increase this risk of post-harvest losses.

Crowding out by other crops: Cotton is still not perceived as an economically important crop and is generally grown on marginal and abandoned lands. Although cotton has the unique characteristic of being able to survive in challenging environments, in saline and drought-prone areas, and on high slopes. The High Barind Tract is relatively dry, with water scarcity often an obstacle to agricultural production. Climate data shows the area is becoming drier, particularly the higher altitude areas, far from the water table. When cotton cultivation started to be promoted, people were encouraged to grow it on abandoned lands.
In contrast, the Ganges Floodplain has always enough water and the only motivation for farming cotton has been to upgrade farmers’ profit margins. In both areas under study, new crops are emerging that are less labor-intensive, are supported by corporate assistance, and provide higher profit margins (for example, tobacco). To encourage an expansion in cotton farming, there is a need to motivate farmers on cotton’s advantages (see Table 7) and to put in place incentives. Without these actions, cotton fields risk being colonized by new crops.

Table 7. Opportunities and constraints in the cotton value chain.

| Opportunities                                                                 | Constraints                                                                 |
|-------------------------------------------------------------------------------|----------------------------------------------------------------------------|
| ✔ Bangladesh is one of the largest exporters of finished garments as well as the second-largest importer of raw cotton. There is a huge scope to increase domestic cotton production to address the country’s demand for raw cotton [6]. | ✔ Cotton flowers are highly sensitive to rainfall and prone to damage if there is untimely rainfall. |
| ✔ Cotton requires much less water than paddy, which makes it a viable option in the highlands and drought-prone areas [8]. | ✔ Increasing temperatures have led to an increased incidence of pests. |
| ✔ Cotton has saline-tolerant properties that make it a viable crop in areas experiencing saltwater intrusion [22]. | ✔ The cropping period of cotton is long, which lengthens its exposure to climate variability and complicates matching it to an annual crop bundle [8]. |
| ✔ Economically, the crop is viable for small and marginal farmers as the returns are relatively high. | ✔ There is a lack of information on weather forecasts and variability. |
| ✔ All by-products of cotton are useful. Cotton is used for textiles; the seed is used for vegetable oil; the seed residue serves as a protein-rich food for livestock; the plant remnants are used as fuelwood, which is scarce in Bangladesh. | ✔ The processing stage of the cotton value chain is weak, with very few ginners to buy and process the cotton. This is a major hurdle for cotton expansion. |

5.3. Opportunities and Constraints of the Cotton Value Chain

Opportunities and constraints for the growth and development of cotton cultivation in Bangladesh found from the study is briefly discussed here.

6. Conclusions and Recommendations

In the above discussion, we explained the possible impacts of climate change on cotton cultivation in two geographic settings of Bangladesh. The timely and appropriate action to adapt cotton production to respond to the likely impacts of climate change could potentially improve the economic value of cotton, which already has a huge market in Bangladesh’s growing ready-made garments sector. Climate change could have a significant negative impact on production and productivity (yield) of cotton due to low seeding rates, hydric stress of plants due to lack of moisture, the resistance of caterpillars, and declining soil fertility levels. Any or all of these adverse factors would directly affect the income and livelihood security of cotton farmers. In Bangladesh, cotton producers are predominantly from low-income groups that have extremely limited resources to adapt to adverse climatic condition. The consequences of climate change would potentially increase production costs and decrease yields. Consequently, cotton cultivation could result in a decrease in their net income and, in the worst case, debt. Thus, changes in climate conditions would create a potential threat to cotton production in Bangladesh and bring the risk of increased poverty and reduced well-being to cotton farmers in rural areas.

One of the major issues identified in this research is the long duration of cotton cropping. It is extremely important to shorten this crop duration, ideally to a maximum of six months. A farmer who is not growing cotton can often intensify agricultural land use and grow three crops in one year on the same land, thus achieving a better income and enhanced food security. In addition, shorter-duration crops are likely to be more
resilient through reduced exposure to any variability in weather patterns. For example, presently cotton harvesting takes place over several weeks, and cotton is picked in three phases. If improved varieties have two harvesting phases, instead of three, this could reduce the risk of losses from the emerging wet spells in February and March. Addressing this constraint through plant breeding, to develop improved short-season cotton varieties, would encourage farmers to adopt cotton cultivation at a larger scale.

Changing climate and weather patterns will expose cotton farming to new sets of pests, fungi, and other microorganisms. Increased CO\textsubscript{2} in the atmosphere will increase the appetite and fertility of leaf-eating caterpillars. Similarly, increased temperatures will facilitate favorable survival conditions for whiteflies, thrips, aphids, mealybugs, and many other pests [27]. Input service providers must be ready to supply materials to match these changes, along with advice on appropriate integrated pest management practices.

Our climate data analysis indicates that changes in weather patterns are likely to pose a major challenge to cotton farmers in terms of water scarcity because (1) rainfall in September and October is declining, (2) there is a gradual increase in the number of dry spells of four days or more, and (3) the water table is dropping. Therefore, it is important to scale up the promotion of climate-smart irrigation practices, which include (1) increasing the use of organic fertilizers and other organic materials to increase the moisture conservation capacity of the soil significantly; and (2) using water sprinklers instead of flood irrigation to markedly reduce the over-use of scarce irrigation water.

Based on the challenges identified in this study and subsequent localized climate vulnerability analyses, a set of climate-resilient agro-economic practices need to be developed and introduced across the cotton value chain. These practices will address existing socio-economic and agronomic vulnerabilities and improve the resilience of the value chain to climate change. Specifically, there is an urgent need for the development of new, or the promotion of existing, cotton varieties that have a shorter cropping duration and are suited to the specific climatic conditions in which they are grown. Pests and crop diseases need to be regularly monitored and necessary measures to tackle these undertaken. Most importantly, climate data indicate a need for climate-smart irrigation and the use of inputs such as organic manure and fertilizers to optimize sustainable resource use.

Finally, it is important to note that this research was hosted by the Cotton Development Board of Bangladesh and they are using this research to inform their strategies and plans. They also want to replicate this research in other cotton-growing regions to make localized decisions on expanding cotton production. In addition, is probably the first time that a value chain approach has been adopted to understand the impact of climate change on any crop in Bangladesh. Thus, there is a potential for other agricultural departments to use this approach to inform their decision-making. This research was also extremely useful in developing institutional partnerships between the Bangladesh Meteorological Department, CDB, and International Centre for Climate Change and Development (ICCCAD). Going forward, these partnerships can support capacity development in all these organizations and facilitate more informed decisions in the fight against climate change impacts on agriculture in Bangladesh.

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