

Climates' Dual Grip: Mapping Upper and Lower Bounds for Thermal Stress Risk for Rice, Wheat, and Maize in Bangladesh

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RESEARCH SUMMARY

The stability of food production is a major concern, given the impact of climate change, the growing human population, and changing dietary patterns. Variations in climate and extreme weather events can significantly affect the productivity of major cereal crops, which can have significant implications for the income and rural livelihoods of farmers, particularly in regions prone to climate change risks. However, research in this area has been hampered by a lack of readily available data and generalizable interpretations of the effects of weather extremes, which could be used for national climate change preparedness, adaptation, and agricultural decision-making.

This study aims to estimate the probabilities of thermal crop stress thresholds being exceeded for three major cereals - rice, maize, and wheat - grown in different geographical regions of climate change-prone Bangladesh at various phenological stages. We first established temperature stress thresholds for each phenological stage of selected crops through a systematic literature review. We used 36 years of maximum and minimum temperature data from 31 Bangladesh Meteorological Department (BMD) stations, whose datasets were divided into three time-slices: Historical (1982-1999), current (2000-2017), and long-term (1982-2017). We subsequently calculated the probabilities of exceeding low- and high-temperature thresholds for these periods, which were mapped using the best-fitted kriging method to interpolate surfaces. The generated map surfaces were masked with potential crop suitability maps to identify the high and low temperature risk zones corresponding to each crop.

The results indicate that the likelihood of low temperature stress exceeding thresholds during the grain-filling stage of early-sown winter '*rabi*' season maize, and high temperature stress during the grain-filling stage of late-sown maize, is high and widespread across west, north-west, and north-east areas of the country. Low temperature stress during grain filling is also highly probable for wheat. Furthermore, wheat is susceptible to stress from both low and high temperatures during the flowering stage. Winter '*boro*' season rice is also susceptible to low temperature stress during sowing, germination, and the seedling stage, regardless of the climatic period and sowing time. During the heading, flowering, and ripening stages, *boro* is also likely to experience stress from high temperatures. The probability of low temperature stress exceeding thresholds for summer monsoon '*aman*' season rice during flowering or grain filling is low to negligible. However, if planted late, significant negative impacts could arise from low temperatures during the heading to flowering and ripening stage. Our analysis indicates no probability of low temperature stress exceeding thresholds during the spring season '*aus*' rice. Conversely, high temperature stress during all phenological stages of *aus* rice is highly probable. Although Bangladesh is a small country, our data suggests that the likelihood of high temperature stress exceeding thresholds for these crops varies across the country, both temporally and spatially. These findings can be useful in designing research on abiotic stresses in Bangladesh, and in advising farmers on crop planning schedules. They can also inform crop modelling efforts, which are crucial in improving crop calendars, crop planning, and crop yield forecasting.

Keywords: Crop phenology, climate risks, exceedance probability, temperature thresholds, crop yield

TABLE OF CONTENTS

1.	Introduction.....	2
2.	Methods	4
2.1	Weather data.....	4
2.2	Determining phenology and growth stages of major cereal crops.....	4
2.3	Procedure for determining thermal stress thresholds.....	7
2.4	Generation of probability of exceedance thermal stress maps.....	9
3.	Results and discussion.....	11
3.1	Thermal stress thresholds	11
3.1.1	Rice	13
3.1.2	Wheat	14
3.1.3	Maize.....	14
3.2	Phenological windows and temperature thresholds for cereals in Bangladesh.....	15
3.3	Thermal thresholds exceedance for various critical development stages of <i>boro</i> rice	16
3.3.1	Sowing and germination	16
3.3.2	Seedling stage	17
3.3.3	Maximum tillering.....	20
3.3.4	Heading and flowering.....	22
3.3.5	Ripening.....	26
3.4	Thermal thresholds exceedance for various critical development stages of <i>aus</i> rice	26
3.4.1	Sowing and germination	26
3.4.2	Seedling stage	27
3.4.3	Maximum tillering.....	28
3.4.4	Heading and flowering.....	31
3.4.5	Ripening.....	32
3.5	Thermal thresholds exceedance for various critical development stages of <i>aman</i> rice	34
3.5.1	Sowing and germination	34
3.5.2	Seedling stage	34
3.5.3	Maximum tillering.....	36
3.5.4	Heading and flowering.....	38
3.5.5	Ripening.....	39
3.6	Thermal thresholds exceedance for various critical development stages for wheat ..	41
3.6.1	Sowing and germination stage.....	41
3.6.2	Vegetative stage	42
3.6.3	Heading and flowering.....	45
3.6.4	Grain filling	50
3.7	Thermal thresholds exceedance for various critical development stages of maize ...	50
3.7.1	Sowing and germination	50
3.7.2	Vegetative stage	53
3.7.3	Silking and tasselling	54
3.7.4	Grain-filling stage	55
4.	Practical application of this study's findings.....	58
4.1	Temperature sensitivity and exceedance of threshold temperatures in rice	59
4.1.1	Boro rice	59
4.1.2	Aus rice.....	59
4.1.3	Aman rice	59
4.2	Temperature sensitivity and exceedance of threshold temperatures in wheat	60
4.3	Temperature sensitivity and exceedance of threshold temperatures in maize.....	61
4.3.1	Management strategies in cereals to alleviate temperature stresses.....	61
5.	Conclusions.....	64
	Acknowledgements	64
	References.....	65
	Annex I. Papers used in systematic literature review to determine temperature stress thresholds for rice, wheat and maize.	71

1. INTRODUCTION

Global climate change is a significant challenge to future food production due to the associated increasing occurrence of extreme weather events (Arshad et al., 2016; Lobell et al., 2008), since the rise in global temperatures is leading to a higher frequency of extremely hot days (IPCC, 2013; Zhao et al., 2017). According to research, global temperatures are predicted to increase by approximately 1 and 3 °C by 2025 and 2100 respectively, compared to levels measured in 1999 (Jones et al., 1999). Recent predictions suggest that mean global temperatures may rise by up to 2 °C between 2046 and 2065, accompanied by an increase in the frequency and intensity of extreme heat events (IPCC, 2013). These changes in extreme events can significantly impact the productivity of rice, wheat, and maize, the three primary cereals providing a major portion of the global population's calorie intake. These changes have already led to reductions in wheat yields and are expected to reduce negatively impact wheat, maize and rice yields (Ceccarelli et al., 2010; Lobell et al., 2008).

High temperatures during rice flowering can lead to spikelet sterility and yield reductions (Jagadish et al., 2007). In several wheat-producing regions, particularly in tropical areas where smallholder farmers operate, high temperatures during grain filling stages can cause significant yield reductions (Asseng et al., 2011). Through model ensembles, Asseng et al. (2015) predicted that global wheat production could decline by 6% with each 1 °C rise in temperature, making wheat production increasingly unpredictable across space and time. Both low and high temperatures can adversely affect rice and maize crops, which are grown throughout the year in many tropical and sub-tropical environments (Hatfield, 2015; Ramirez-Cabral et al., 2017; Waqas et al., 2021; Yoshida, 1981). Low temperatures can occur during germination, seedling, and vegetative stages in many environments where winter season wheat, maize, and rice are cultivated (Kabir et al., 2015; Kihachi et al., 1999; Ramirez-Cabral et al., 2017; Waqas et al., 2021), potentially reducing returns on farmers' investment in crop production and contributing to poverty traps in tropical and sub-tropical areas (Brown and Funk, 2008; Batisti et al., 2009; Ray et al., 2015).

Crop growth and phenological development can be influenced by both low and high temperatures, which depend on crop species, varieties, and time of sowing or planting, as well as management factors such as irrigation (Jones et al., 1999). At the species level, each crop has a temperature range for optimal growth during different stages. Deviations from this range, whether below or above, can have adverse effects on growth, development, and grain yield of cereals (Angus et al., 1981; Hatfield, 2015; Porter and Gawith, 1999). Temperatures below the optimum can slow the development process, lengthening the growth duration, and contributing to grain sterility. Conversely, temperatures above the optimum can accelerate phenological development, resulting in a shorter growth period and reduced grain yield in all cereals (Hatfield, 2015). Researchers have attempted to determine minimum and maximum temperature thresholds for each growth stage of each crop (Luo, 2011).

Although much research has been conducted to describe the risks of exceeding minimum and maximum temperature thresholds for major cereals grown in many

countries, studies in smaller geographical areas in the sub-tropics remain limited. Moreover, the use of observed historical data in informing agricultural climate services is under-represented in research, and there is much that can be learned in this area (Mason et al. 2022). Understanding the effects of low and high temperatures on cereal productivity and determining the probabilities of exceeding their thresholds within a country are critical for climate change adaptation planning and developing strategies for sustainable cereal production. Such understanding can improve the use of gridded crop simulation models that can study the long-term effects of climate change (Asseng et al., 2011, 2015) while isolating climate from other crop production factors that affect yield (Lobell et al., 2008; Asseng et al., 2011).

Bangladesh, a deltaic country located in South Asia with multiple crop growing seasons in a single year, was one of the top 13 most vulnerable countries in the world in 2020 because of its frequent exposure to natural hazards and climate change (Alliance Development Works, 2020). Cereals grown in sub-tropical Bangladesh suffer from high and low temperature stresses at different growth stages. Rice is the dominant cereal crop followed by wheat and maize grown in Bangladesh. About 75% of the gross cropped area (GCA) in Bangladesh is occupied by rice. Wheat and maize are grown as winter, '*rabi*' season crops, occupying about 2.06% and 3.00% of the GCA respectively (BBS, 2023). There are three crop growing seasons in Bangladesh: *rabi* (winter; November to March), '*kharif*-1 (pre-*kharif*; March/April-June), and *kharif*-2 (monsoon; July-October). The cropping season in Bangladesh is determined by the seasonal distribution of rainfall, influencing farmers' crop selection.

Rice is grown in all three seasons and is respectively known as winter season '*boro*', spring-season '*aus*', and summer season '*aman*' when grown during *rabi*, *kharif*-1 and *kharif*-2. Aman rice in *kharif*-2 is usually sown with the beginning of the first rain in July when the southwest monsoon arrives. Boro rice and *rabi* maize are grown in the *rabi*, winter season under full irrigation while about 80% of wheat, also grown in *rabi*, is either partially or fully irrigated with a very limited amount grown as rainfed. Aus rice and *kharif*-1 maize are mostly grown under rainfed condition, though with the expansion of irrigation facilities *kharif*-1 maize is also grown under irrigation. The pre-*kharif* or *kharif*-1 season is characterized by high temperature, stormy rainfall, and humidity (Hassan and Sys, 1986); it differs from the other two seasons by undependable rainfall which varies in timing, frequency, and intensity from year to year and provides only an intermittent supply of moisture for the standing crops. The transition period between dry *rabi* and wet *kharif* seasons and its relative length depends on the timing and intensity of pre-monsoon rainfall, which is affected in part by geography.

In no country worldwide do farmers sow seeds or plant seedlings of a particular crop or variety on the same date. Instead, sowing or planting varies with location, climatic conditions, and/or farmers' socio-economic circumstances, resulting in a wide planting window and different establishment times for each crop. Variations in sowing or planting could lead to differences in low and high temperature stresses at different

growth stages of the crops, resulting in significant variations in crop growing periods. Given the large temporal and spatial variability in historical climate datasets, the main objective of the study was to identify generalizable thermal stress thresholds for different phenological stages for the three major cereals in Bangladesh. Another objective was to identify regions within Bangladesh where the probabilities of exceeding temperature thresholds are greater or less than the thresholds at different growth stages of these cereals, using historical climate data.

2. METHODS

2.1 Weather data

Currently, the Bangladesh Meteorological Department (BMD) has 46 synoptic weather stations that are in operation. Among them, 18 were established before 1947, 12 before the independence of Bangladesh in 1971, 12 during 1971-1991, and 12 after 2015. The distribution of BMD observatories is shown on the map (Figure 1). In the current study, we used 36 years (1982 -2017) observed daily maximum and minimum temperature data from 31 selected synoptic weather stations from which we could retrieve daily, unbroken temperature measurements.

2.2 Phenology and growth stages of major cereal crops in Bangladesh

There are typically large north-south gradients in the timing of crop establishment in Bangladesh. Agricultural land use at a local level is determined by land type or flooding regime, onset of monsoon, availability of irrigation, and the spatial and temporal distribution of crops or cropping patterns. Cropping pattern, on the other hand, depends on the physiography, agricultural land availability, environment, and socioeconomic conditions of a particular area (Nasim et al. 2017, Hasan et al. 2013, Shahidullah et al. 2006). In addition to crop sowing/planting or (rice) transplanting dates, the phenology of field crops also varies with the duration of the crop in question, which is strongly affected by the cultivar grown by farmers (BRRI, 2019; BARI, 2019; BINA, 2017).

The agricultural system in Bangladesh is highly complex, with a wide range of factors affecting crop growth and development. One such factor is the diversity of sowing or transplanting dates, which can vary significantly even between neighbouring fields. For example, two farmers growing the same variety of rice may establish their crops several weeks apart. Despite this, both farmers may achieve maturity at a similar time, with the late transplanting farmer growing a short-duration cultivar and the earlier transplanting farmer growing an intermediate-duration variety. Conversely, farmers located far apart from each other may establish their crops on the same day. Moreover, there is substantial varietal diversity among crop species grown in Bangladesh, with 108 rice (101 inbreds and 7 hybrids) varieties released by the Bangladesh Rice Research Institute (BRRI, 2022), and potentially hundreds of additional local varieties grown by farmers (Kamruzzaman, et al. 2017).

Due to the diverse range of varieties available, the number of days required to reach specific phenological stages can vary significantly among crops. For instance, *boro* rice sowing typically commences during November and December,

but it can extend to late January. The germination period for *boro* rice seeds is typically 3-5 days, and it takes approximately 40-45 days for seedlings to reach transplanting readiness, which usually occurs between mid-December and mid-February throughout the country. Transplanted rice seedlings usually experience transplanting shock, and it takes about 7-10 more days for them to recover fully. Boro rice generally achieves maximum tillering within 40-50 days, followed by booting and flowering, each requiring approximately ten days. Finally, ripening and maturity typically occur together and take 25 to 30 days, depending on the cultivar and the prevailing climate.

Table 1 summarizes the general periods of different phenological stages for rice, wheat, and maize grown across Bangladesh. This information was obtained through consultations with scientists from the Bangladesh Rice Research Institute and Bangladesh Agricultural Research Institute during workshops held in 2018 and 2019. The phenological stages and approximate number of days required to reach a particular stage for rice (Yoshida, 1981; IRRI, 2018), wheat (Large, 1954; Acevedo et al., 2002), and maize (Pringle, 2017) were estimated based on published literature and presented to meeting participants. They then reached a general consensus on the generalized crop periods.



Above: Farmers preparing rice seedlings for machine transplanting in Bangladesh. Photo Credit: Abdul Momin.

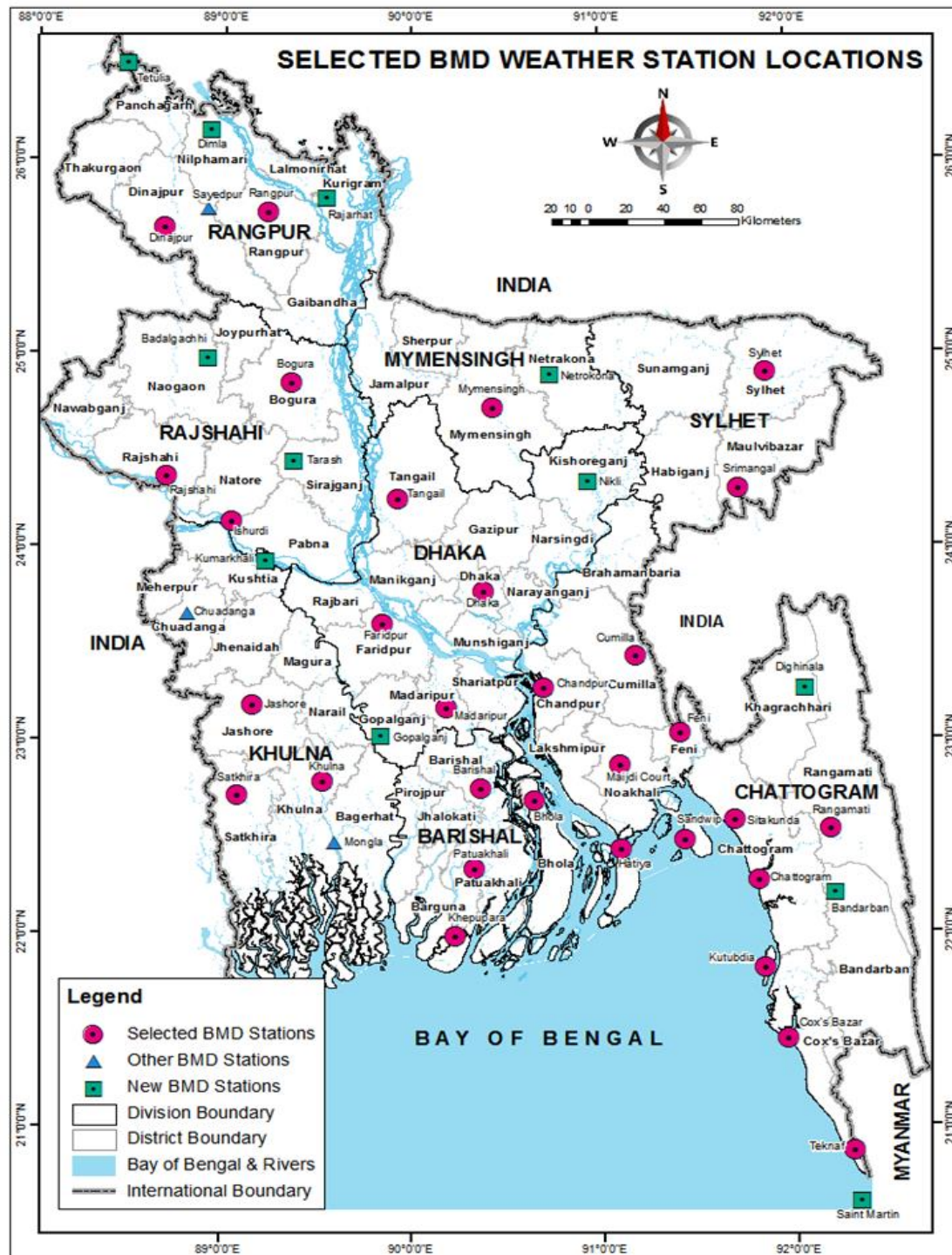


Figure 1. Locations of selected weather stations of Bangladesh Meteorological Department. Stations selected included those with an unbroken history of minimum and maximum temperature data from 1982-2017.

2.3 Defining thermal stress thresholds for wheat, rice and maize

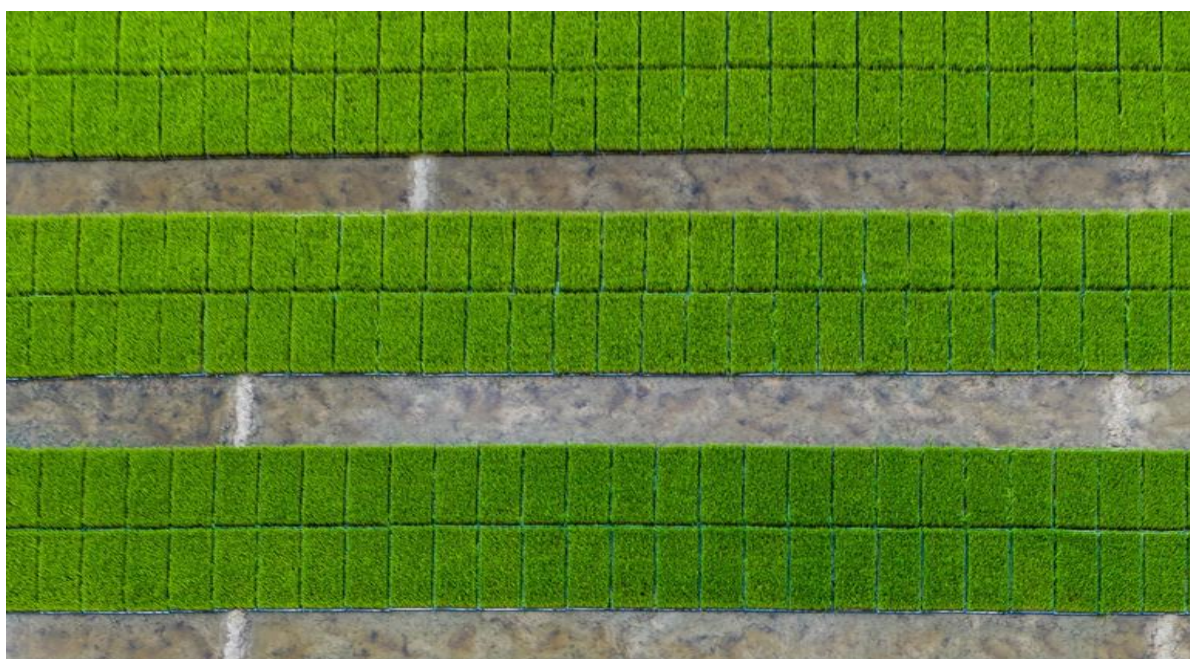
A systematic literature review was undertaken using Scopus, Web of Science, CAB Direct and AGRICOLA

databases to identify low and high temperature stress thresholds for rice, wheat and maize in Bangladesh. For this, a comprehensive strings of database-specific search queries/criteria were used to summarize those thermal thresholds, which could also be applied to similar tropical and sub-tropical environments in other countries globally.

When searching for grey literature, the same key search terms were employed as used in the Scopus database. The following search string serves as an example of a query applied in the Scopus database.

(TITLE-ABS-KEY (heat OR "high temp*" _OR "high-temp*" _OR "heat stress" _OR "heat-stress" _OR "thermal stress" _OR "thermal-stress" _OR cold OR "cold temp*" _OR "cold-temp*" _OR "cold stress" _OR "cold-stress" _OR "terminal heat stress" _OR "terminal heat-stress" _OR "terminal heat" _) AND ABS ("zea mays" OR maize OR corn OR "triticum aestivum" OR wheat OR "oryza sativa" OR rice) AND ABS (yield)

In this search string TITLE-ABS-KEY means a search in the title, abstract, and keywords fields, * replaces zero or more characters or truncates the search item, and ABS means a search in the abstract, while OR and AND are operators. Resulting citations were stored in EndNote (Ver 8, Clarivate Analytics) (Figure 2).



Above: Rice seedling trays in Bangladesh shown from above. Photo Credit: Adbul Momin

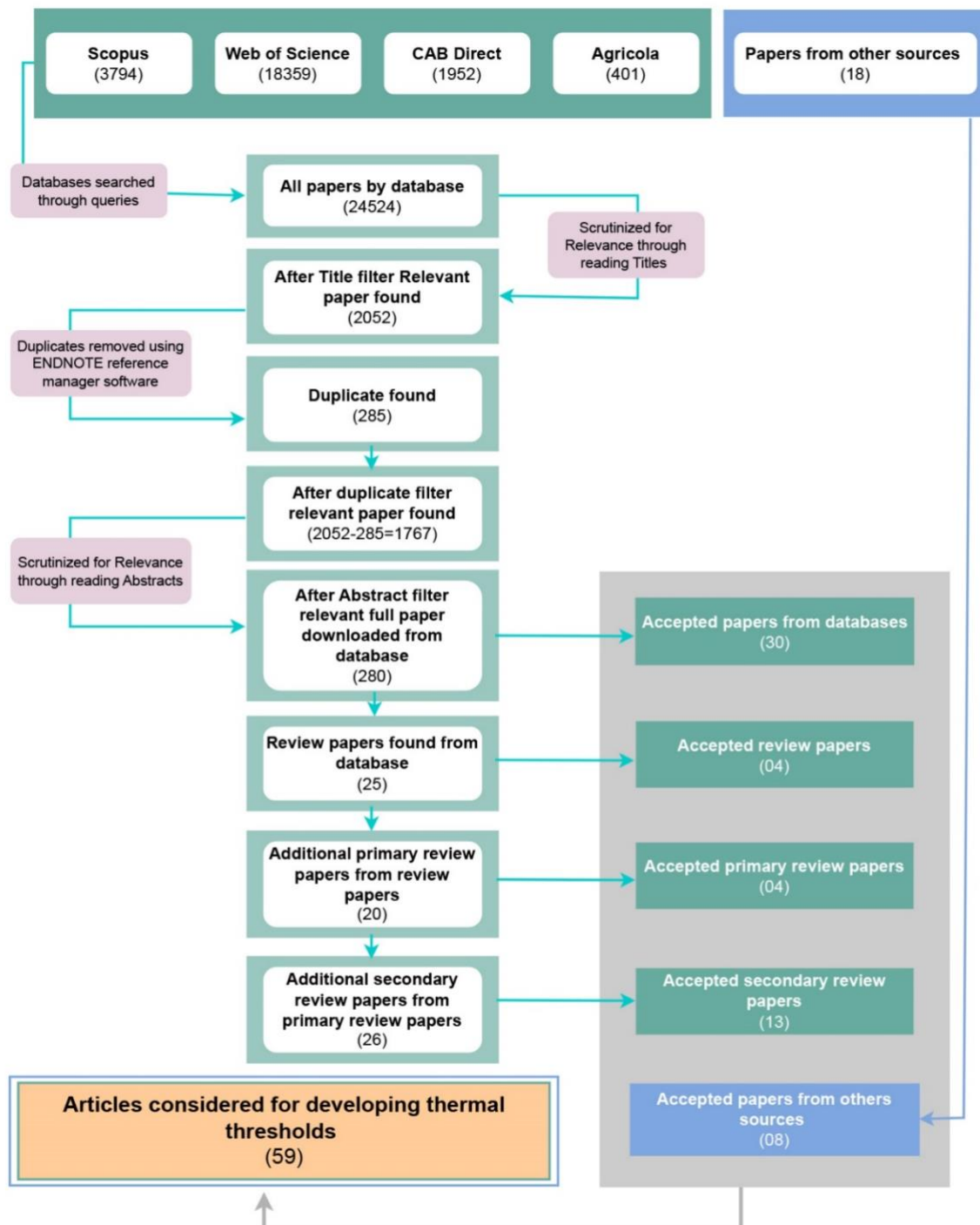


Figure 2. The methodological process utilized in the systematic literature review aimed to identify peer-reviewed papers from which data on rice, wheat, and maize stress thresholds were extracted. The figures presented in parentheses denote the number of papers that were identified during the search and the number that were ultimately retained for data extraction.

After carefully evaluating the titles of 22,454 articles, we excluded those that fell outside the scope of our study. We then removed duplicate articles, resulting in 1,767 papers. We examined the abstracts of these papers to identify studies that quantitatively demonstrated thermal stress thresholds, specifically focusing on high- and/or low-temperature thresholds for each crop at different phenological stages. To ensure the reliability of the results, we included only field studies that involved experimental manipulation or field-specific observations of temperature immediately above the canopy, as there is a potential for experimental artifacts in growth chambers. After applying these criteria, we identified 280 papers that were downloaded and reviewed. In addition to these papers, we found 25 more relevant studies from the bibliography section of the downloaded papers.

Furthermore, we identified 20 primary review papers in the database that included acceptable measurements of high or low temperature stresses. We also found 26 more secondary review papers that contained data from primary review literature. After a thorough examination for experimental consistency and data reliability, we finally selected 59 papers that were useful for determining low- and high-temperature thresholds. References for papers used to develop the temperature thresholds are given in Annex I.

Following the literature search, the extracted data were compiled into a spreadsheet and analyzed to examine the correlation between crop species yield performance and temperature. This analysis resulted in the creation of scatter plots that allowed for the visualization of the data. Subsequently, the temperature data obtained from the scatter plots were analyzed to identify the thresholds at which a decline in yield was observed during specific phenological stages.

In instances where the papers only reported a single temperature value as a threshold for yield decline, that value was accepted as an indicator of either the maximum or minimum stress threshold. This approach was adopted due to the absence of clear reporting of high- or low-temperature thresholds in some studies. The adopted methodology ensured the reliability and accuracy of the results obtained from the data analysis.

2.4 Generation of probability of exceedance thermal stress maps

For each phenological stage and for each of the 31 weather stations in Bangladesh Meteorological Department (BMD), we utilized 36 years of maximum and minimum temperature data, spanning from 1982 to 2017. The climatic periods were defined based on expert consultations, as described in Section 2.3. The three climatic periods considered were: Historical (1982-1999), recent (2000-2017), and long-term (1982-2017).

To construct a spatially interpolated temperature dataset, daily maximum and minimum temperature data from each of the 31 BMD stations were used for each day of the year during these periods. The best-fitted kriging method was employed to create a daily 0.5 km × 0.5 km spatial resolution grid of maximum and minimum temperature.

For all three climatic periods, we constructed cumulative density functions for the maximum and minimum temperatures for grid cell. From the threshold values that are provided in Table 2, we determined the probabilities of low- and high-temperature exceedance in percentages for each grid cell. From these probabilities, we generated interpolated surfaces for each phenological period, and each crop considered in this study for entire Bangladesh. The spatial interpolation was performed using an ordinary kriging algorithm and Best-fitted variogram. The changes between three periods were later presented as spatial plots. Shape files from BARC (Hussain, et al., 2012) were used to mask out the unsuitable areas on the generated maps. Each spatial plot was generated in a 0.5 km by 0.5 km spatial resolution. Open-source software RStudio was used for scripting. The codes to generate cumulative density functions (CDFs) are provided in GitHub (Faisal and Hasan, 2023).

A high-level overview of this process is shown in Figure 3 and is described below in detail. After selection of input (weather) data from the BMD stations, the preprocessing is done by filtering the weather data for the time slices, obtaining the required date range for a particular growth period; and then by selecting the values for temperature threshold (upper/lower). The system then calculates the cumulative probability distribution function (CDF). The system then interpolates the data by ordinary kriging method. At this stage, the system fits the data with different variogram models and calculates the residuals, after which the system automatically chooses the model with lowest residuals. Models that are used to fit the data included the spherical model (Supergeo Technologies Inc., 2017a), the exponential model (Supergeo Technologies Inc., 2017b), the Gaussian model (Supergeo Technologies Inc., 2017c); and Matern, M. Stein's parameterization (Stein, 1999). After the calculation of the CDF, the system generates maps of thermal stress threshold surfaces. This step includes clipping the generated maps with country boundary, river streams, etc. After the map generation, we next masked the maps by crop regions in the country. This generated the final output in the form of a national map.



Above: A nursery for machine transplanted rice in Bangladesh. Photo credit: Abdul Momin

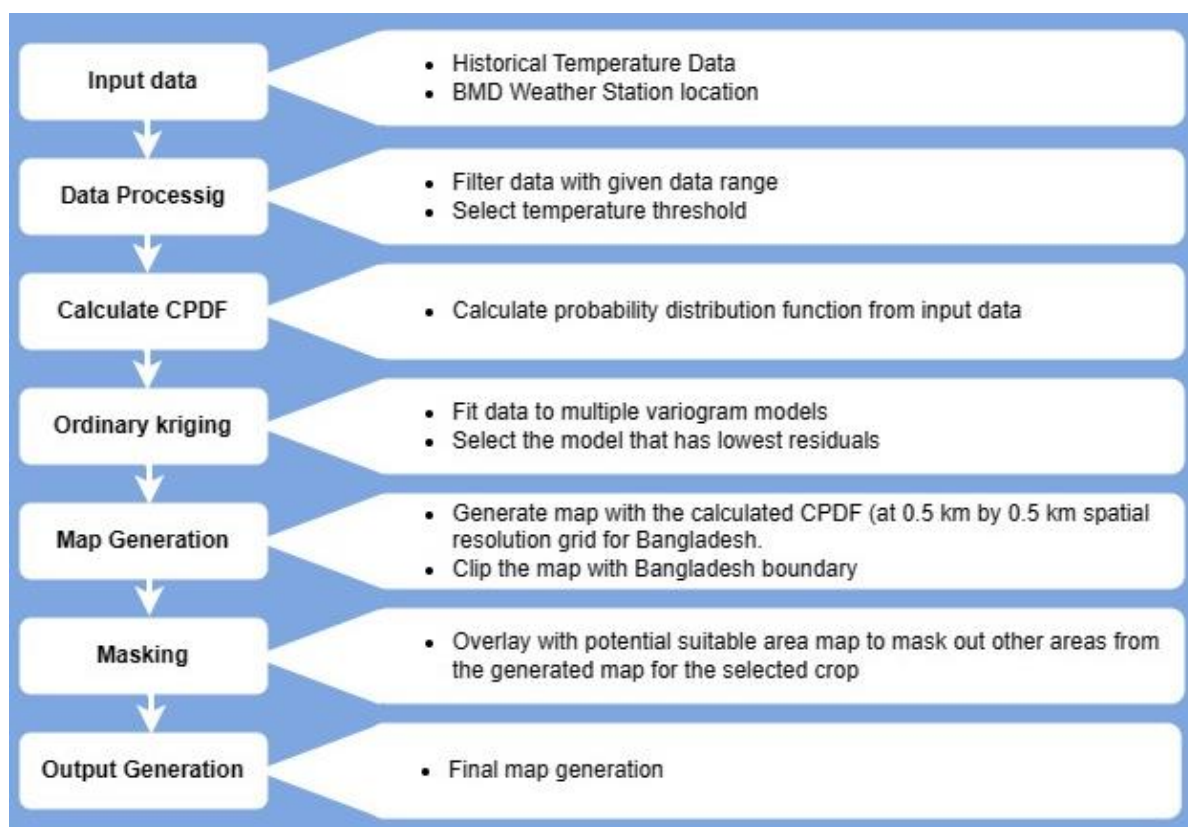


Figure 3. Simplified methodology for generation of probability of exceedance thermal thresholds maps for Bangladesh. CDF indicates cumulative distribution function; CPDF indicates calculate probability density function.

3. RESULTS AND DISCUSSION

Each crop has an upper and lower threshold for temperature tolerance. Also, individual stresses cannot be viewed in isolation; for example, the upper threshold for temperature may vary depending on the minimum temperatures experienced over the same time period and vice versa (Kabir et al., 2015). The extent of damage is also dependent on the duration of exposure to extreme temperatures (Kabir et al., 2015). In addition, it should be noted that when using air temperature for thresholds that these temperatures can differ considerably from canopy temperature (Rezaei et al., 2015; Siebert et al., 2014) due to a range of biotic and abiotic factors (e.g. canopy architecture, wind speed, soil moisture). Crop models to date have incorporated the effects of air temperature and not canopy temperature and thus limiting the accuracy in predicting crop response to temperature. Understanding the crop response to canopy temperatures will help develop robust mechanistic crop growth simulation models (Rezaei et al., 2015).

3.1 Thermal stress thresholds

Table 1 presents phenological windows and temperature thresholds identified through systematic literature review for different stages for the three cereal crops and applied to Bangladesh.

Table 1. Phenological windows of major cereal crops in Bangladesh with estimates of the number of days required for each stage and temperature thresholds.

Crop	Phenological stage	Start date	End date	Approximate stage to stage duration (days)	n	Temperature (T) threshold	
						T Min (°C)	T Max (°C)
Boro rice	Sowing and Germination	31-Oct	31-Dec	5	1, 1	10.0	40.0
	Seedling	10-Dec	27-Jan	40	1, 24	10.0	35.0
	Maximum tillering	29-Jan	1-Apr	40-45	1, 1	10.0	35.0
	Heading and flowering	28-Feb	25-Apr	13-15	16, 45	17.0	35.0
	Ripening	20-Mar	11-May	15-20	5, 9	12.0	33.0
Approximate seed to seed duration				140-155			
Aus rice	Sowing and Germination	20-Mar	25-Apr	0	1, 1	10.0	40.0
	Seedling	11-Apr	17-May	20	1, 24	10.0	35.0
	Maximum tillering	23-May	23-Jun	30-35	1, 1	10.0	35.0
	Heading and flowering	17-Jun	17-Jul	12	16, 45	17.0	35.0
	Ripening	3-Jul	30-Jul	13-16	5, 9	12.0	33.0
Approximate seed to seed duration				106-115			
Aman rice	Sowing and Germination	20-Jun	31-Jul	0	1, 1	10.0	40.0
	Seedling	17-Jul	3-Sep	25-32	1, 24	10.0	35.0
	Maximum Tillering	11-Sep	21-Oct	40-50	1, 1	10.0	35.0
	Heading and flowering	6-Oct	15-Nov	12	16, 45	17.0	35.0
	Ripening	22-Oct	1-Dec	16	5, 9	12.0	33.0
Approximate seed to seed duration				134			
Wheat	Sowing	1-Nov	30-Dec	0	2, 1	3.0	33.0
	Vegetative	6-Dec	3-Feb	35	0, 1	6.4	30.0
	Heading and Flowering	16-Dec	13-Feb	5	4, 41	6.4	32.0
	Grain filling	5-Jan	5-Mar	20	2, 18	8.5	32.0
Approximate seed to seed duration							
Maize	Sowing and Germination	15-Oct	13-Jan	0	1, 1	8.0	40.0
	Vegetative	15-Dec	7-Mar	55	2, 3	7.5	35.0
	Flowering	29-Dec	22-Mar	15	1, 15	10.0	35.0
	Grain filling	2-Feb	29-Apr	15	2, 2	15.0	33.0
Approximate seed to seed duration							

1. All values are approximations, as the values may vary over years, production environments, and locations.
2. The column 'n' with indicates the number of study observations included to calculate thresholds where the first number is minimum and the second is maximum temperature thresholds derived from the systematic literature review.

The temperature thresholds were considered as the prime driver of the analysis. Phenological windows for rice, wheat, and maize in Bangladesh with estimates of the number of days required for each stage and maximum (upper) and minimum (lower) temperature thresholds are also shown in this table. Table 2 summarizes the low and high temperature thresholds for the three cereal crops.

Table 2. Minimum (Min) and maximum (Max) temperature (T) thresholds for rice, wheat, and maize at different phenological stages. Numbers in parentheses are the standard deviation.

	Seedbeds / Seedling		Early vegetative		Flowering		Grain filling	
	T Min (°C)	T Max (°C)	T Min (°C)	T Max (°C)	T Min (°C)	T Max (°C)	T Min (°C)	T Max(°C)
Rice	10.0 (0)	35.5 (0)	10.0 (0)	35.2 (0.6)	17.1 (0.9)	35.1 (0.4)	12.0 (0)	33.1 (0.11)
Wheat	2.9 (0.45)	35.0 (0)	0 (0)	30.0 (0)	6.4 (1.3)	31.4 (0.2)	8.8 (0.05)	32.8 (0.3)
Maize	5.0 (0)	33.0 (0)	7.5 (1.5)	35.0 (1.7)	10.0 (0)	34.8 (0.2)	15.0 (0)	33 (1)

3.1.1 Rice

Rice is sensitive to low temperatures during vegetative (seedling or early growth stages) as well as reproductive (panicle initiation and flowering) growth stages (Jagadish et al., 2007; Yoshida, 1981). On the other hand, rice is sensitive to high day-time temperature ($>32^{\circ}\text{C}$), especially during the reproductive stage. This can result in faster development, shorter reproductive duration, and lower yield (Ishimaru et al., 2010; Islam, 2011; Jagadish et al., 2007; Krishnan et al., 2011; Rezaei et al., 2015; Yoshida, 1981). Rice is also sensitive to high night-time temperature of above 30°C , which reduces leaf photosynthesis and increases plant respiration (Alvarado-Sanabria et al., 2017; Peng et al., 2004), or can result in yield decline of $\sim 10\%$ for each 1°C rise in minimum temperature (Peng et al., 2004). Most literature considering low temperature stresses on rice yield in Bangladesh is relevant to *boro* rice, which can be exposed to temperatures below 10°C during December and January in seedbeds or shortly after transplanting and if low temperatures are prolonged (i.e., > 7 days), they can result in complete crop failure (Ahmed et al., 2016; Kabir et al., 2015). On the other hand, rice can experience high temperature stress at the reproductive stage from panicle initiation to grain formation in many rice-growing environments globally. A critical high temperature threshold of 33°C at flowering stage can increase grain sterility, reduce grain-filling duration, and reduce yield (Bheemanahalli et al. 2016). Exposure to temperatures exceeding 30°C for 7-10 days before anthesis can lead to pollen and spikelet sterility as well as embryo abortion, which ultimately results in lower crop yields. (Krishnan et al., 2011; Reynolds et al., 2016; Shah et al., 2011).

Aus rice can be exposed to high temperatures ($> 35^{\circ}\text{C}$) from end of March to early May coinciding with anthesis and during grain formation and grain filling (Maniruzzaman et al., 2018). Both can be detrimental to yield (Ishimaru et al., 2010; Jagadish et al., 2007; Krishnan et al., 2011; Yoshida, 1981). The sowing of *aman* rice is usually timed with the onset of the monsoon, as farmers wait for sufficient rain to allow paddy field preparation. Regular rainfall events result in lower temperatures maximum being between 29 and 35°C , which are around or only slightly above optimum conditions. Aman rice also experiences high temperature stress during reproductive stage resulting in reduced yield (Amin et al., 2015; Maniruzzaman et al., 2018). In addition to high temperatures, cloudy weather and decreased solar radiation during the monsoon is likely to depress yield depending on the

photosensitivity of the variety (Rahman and Zhang, 2013). Neither *aus* nor *aman* rice however is likely to experience minimum temperatures.

3.1.2 Wheat

Wheat, like other crops, has specific cardinal temperatures for each growth stage. In Bangladesh, supra-optimal temperatures during February and March at the end of the Rabi season are the main temperature-related problems. Farooq et al. (2011) investigated the effects of heat stress on wheat during the reproductive and grain filling stages and found that diurnal minimum and maximum temperatures of 12 °C and 22 °C, respectively, were optimal for these stages. Heat stress resulting from temperatures above 30 °C during floret formation or reproductive phases can cause a reduction in leaf photosynthesis, increased respiration, accelerated senescence, tissue dehydration, and pollen and grain sterility (Farooq et al., 2011; Lobell et al., 2008, 2012; Reynolds et al., 1994; Rezaei et al., 2015). When temperatures exceed 32 °C prior to and during anthesis, photosynthesis declines, leading to pollen sterility, stigma dehydration, reduced seed size, and lower seed setting (Farooq et al., 2011; Lobell et al., 2012; Reynolds et al., 2016; Shah et al., 2011). Lobell et al. (2008) estimated that a 1 °C rise in temperature during grain-filling period leads to a 3-17% decrease in yield. Porter and Gawith (1999) reported that when maximum temperatures rise above 34 °C, leaf senescence in wheat accelerates by threefold, and when above 40 °C, it accelerates by six-fold. A modelling study in Australia showed that leaf senescence is a major cause of loss of grain production in wheat, reducing yield by as much as 50% due to observed variations in average growing-season temperatures of ± 2 °C (Asseng et al., 2011). In addition to grain quantity, high temperatures also affect grain quality. Wardlaw et al. (2002) reported that high temperature during grain filling can degrade the flour and bread quality and other physio-chemical properties, including changes in protein content in wheat.

It is not just higher maximum temperatures that are a problem but also increasing minimum temperatures, which may have an even greater impact on wheat yield (Farooq et al., 2011). Night temperatures above 20 °C can reduce spikelet fertility and the grain-filling period by up a week (Prasad et al., 2008). Higher than average night-time temperatures can also increase respiration rates, resulting in a negative impact on grain yield where adequate water is not supplied (Pask et al., 2014; Prasad et al., 2008). An increase in average temperatures above approximately 27 °C can shorten the duration of grain-filling, which can result in a decrease in wheat yield (Rezaei et al., 2015; Tashiro and Wardlaw, 1989). In South Asia, where high temperature stress is common, early maturity is a better adaptation strategy (Mondal et al., 2013). Furthermore, Mondal et al. (2016) found that there is a significant negative association between grain yield and mean minimum temperatures in temperate environments with cooler climates and mean maximum temperatures in tropical environments with hotter climates, during the grain-filling period.

3.1.3 Maize

Both low and high temperatures can have detrimental effects on maize yield. Unlike rice, maize does not tolerate prolonged periods of temperatures below 10

°C (Yadav et al., 2015). Changes in growth rate, photosynthesis, dry matter accumulation, cellular membranes, and antioxidant enzyme activities can all limit maize productivity under low temperature (Waqas et al., 2021). Maize is however comparatively tolerant to high temperatures with the optimum range for photosynthesis being between 33 to 38 °C (Yadav et al., 2016). High temperatures at the vegetative stage improved net leaf photosynthesis rate and stover production but decreased yield by 13% in studies conducted India (Yadav et al., 2015). High temperature stress limits pollen viability and silk receptivity, leading to a significant loss in seed setting and grain yield (Waqas et al., 2021). High temperatures at grain filling stage can however decrease yield due to the temperature sensitivity associated with a number of processes that affect grain number and the duration of grain filling (Dupuis and Dumas, 1990; Jones et al., 1984; Rezaei et al., 2015; Schoper et al., 1987; Yadav et al., 2016). Waqas et al. (2021) reported that maize plants are sensitive to heat stress (>30 °C) and there is a strong decline in grain yield as plants are subjected heat stress above this threshold for a prolonged duration. The optimal growth of maize crop needs different temperatures during day and night and over the whole growing season. During daylight, the optimal temperature varies from 25 to 33 °C, whereas during the night, optimal temperature varies from 17 to 23 °C. The mean optimal temperature for the whole growing season is 20–22 °C. Maize plants germinate best at 25 to 28 °C. The reproductive stage is the most sensitive to sub-optimal and supra-optimal temperatures. Positive deviation from optimal temperature regimes causing high-temperature stress significantly decreases the growth rate and grain yield through a decrease in seed setting ratio and disturbance of several physiological processes. A high temperature at critical development stages may also deteriorate the quality of maize grains.

3.2 Phenological windows and temperature thresholds for cereals in Bangladesh

To calculate the probabilities of thermal threshold exceedance, we considered three climatic periods: 1982-1999, 2000-2017, and 1982-2017. We considered that *boro* rice is sown early, at the optimum time or late, between October 31 and November 15, November 15 and December 16, and December 16-31, respectively, across Bangladesh, as based on expert consultation. For *aus* rice, the sowing ranges for early, optimum, and late are 20-29 March, 29 March-7 April, and 16-25 April, respectively. Aman rice is sown between June 20 and July 31, depending on whether it is early, optimum, or late. For all types of rice, the lower and upper temperature thresholds for different stages range between 10 and 40 °C, 10 and 35 °C, 10 and 35 °C, 17 and 35 °C, and 12 and 33 °C at sowing and germination, seedling, maximum tillering, heading and flowering, and grain-filling stages, respectively. The sowing dates for wheat across the country are November 1-14, November 15-30, and December 15-30 for early, optimum, and late sowing, respectively. The temperature thresholds for wheat at sowing and germination, vegetative, heading and flowering, and grain-filling stages range from 3 to 33 °C, 6.4 to 30 °C, 6.4 to 32 °C, and 8.5 to 32 °C, respectively. For maize, the sowing ranges for early, optimum, and late sowing across the country are October 15-November 14, November 15-December 15, and December 16-January 13, respectively. The temperature thresholds for maize at sowing and germination, vegetative, silking and tasseling,

grain-filling, and ripening stages range between 5 and 22 °C, 7.5 and 35 °C, 10 and 35 °C, and 15 and 33°C, respectively, based on our systematic literature review.

3.3 Thermal thresholds exceedance for various critical development stages of boro rice

3.3.1 Sowing and germination

The minimum temperature threshold of *boro* rice at the sowing and germination stage was identified as 10 °C (Table 2). The probability of lower temperature threshold for the three periods of climate data in all districts showed that the early sowing (31 Oct to 15 Nov) of *boro* seeds could help farmers to escape the low temperature threshold help provide a management alternative to cold stress at sowing and germination. However, sowing during the recommended window of time (15 Nov to 16 Dec) data had a 5-8% chance of exceeding the lower threshold in Chapai Nawbganj in Rajshahi division, four districts in Khulna division, and two districts each in Rangpur and Sylhet divisions, but not in other districts. Similar trends were observed using recent (2000-2017) and long-term (1982-1999) climate data with a slightly lower probability of exceedance (2-3.8 and >3 %, respectively) observed.

On the other hand, risk mapping for late sowing from 16- 31 Dec suggested that the probability of exceeding the low temperature threshold using the historical climate data was between 20-40% for two districts each within Khulna and Sylhet divisions, and five districts within Rangpur division. With the 2000-2017 climate data, the probability of exceeding this threshold was almost half (16-20%) of that of historical climate (1982-1999) for all districts of Rangpur and five districts of Rajshahi division but not for others. With the latter climate data, the probability of exceedance of the low temperature threshold declined further to 12-16% in those districts (Figure 4). The upper temperature threshold at the sowing and germination stage of *boro* rice is 40 °C. Hence, the CDF maps for all three periods of climate data for such thresholds could not be generated since the 40 °C during the sowing and germination stage as this temperature has not been recorded in Bangladesh during this period.



Above: Rice seed being sown into trays used for machine transplanting in Bangladesh. Photo Credit: Abdul Momin

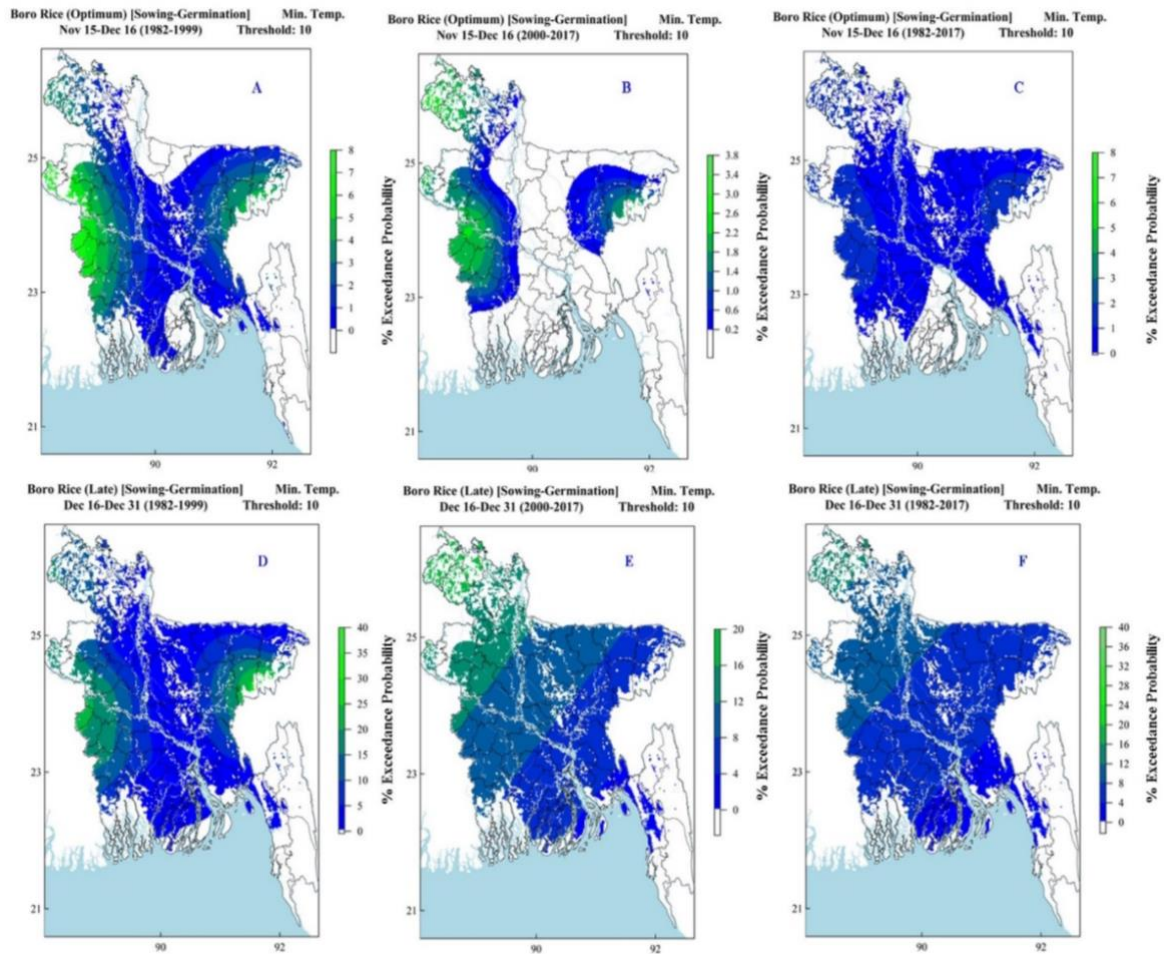


Figure 4. The probabilities of exceeding the low temperature threshold (10°C) during the sowing and germination stage of boro rice were calculated for three time periods: 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term). The probabilities were analysed for early sowing, sowing at optimal or recommended dates, and late sowing. It is worth noting that maps were not generated for simulations that returned zero probability values.

3.3.2 Seedling stage

For the seedling stage and based on our systematic literature review, the lower temperature threshold of rice was identified as 10 °C. When *boro* rice is sown under early (October 31-November 15), optimum (November 16 – December 16), or late (December 16 – 31) conditions and irrespective of the climatic period considered or location, the crop is likely to enter the seedling stage between December 10-26, December 27-January 11, and January 12-27, respectively. When the seeds are sown early, rice seedlings develop during the peak of cold season around 10-26 December and can experience substantial cold stress, particularly in some districts of eastern and southern Bangladesh (Figure 5). The probability of exceeding the

low temperature threshold with historical climate data is between 20 - 40% in the Meherpur and Chuadanga districts of Khulna division and Moulvibazar and Hobiganj districts of Sylhet division. A similar pattern was observed for the recent and long-term climate data, with the probability of exceeding the low temperature threshold of about 16-20% for five districts of Rangpur division, Meherpur and Chuadanga districts of Khulna division, Moulvibazar, and Habiganj of Sylhet division, and Rajshahi, parts of Mymensingh, and Khulna division. However, for rest of the of the country, the probability of exceedance this threshold was 4-8% given available climactic information.



Above: A farmer in Bangladesh displaying rice seedlings grown in trays used to aid in machine-assisted rice transplanting. Photo Credit: Abdul Momin.

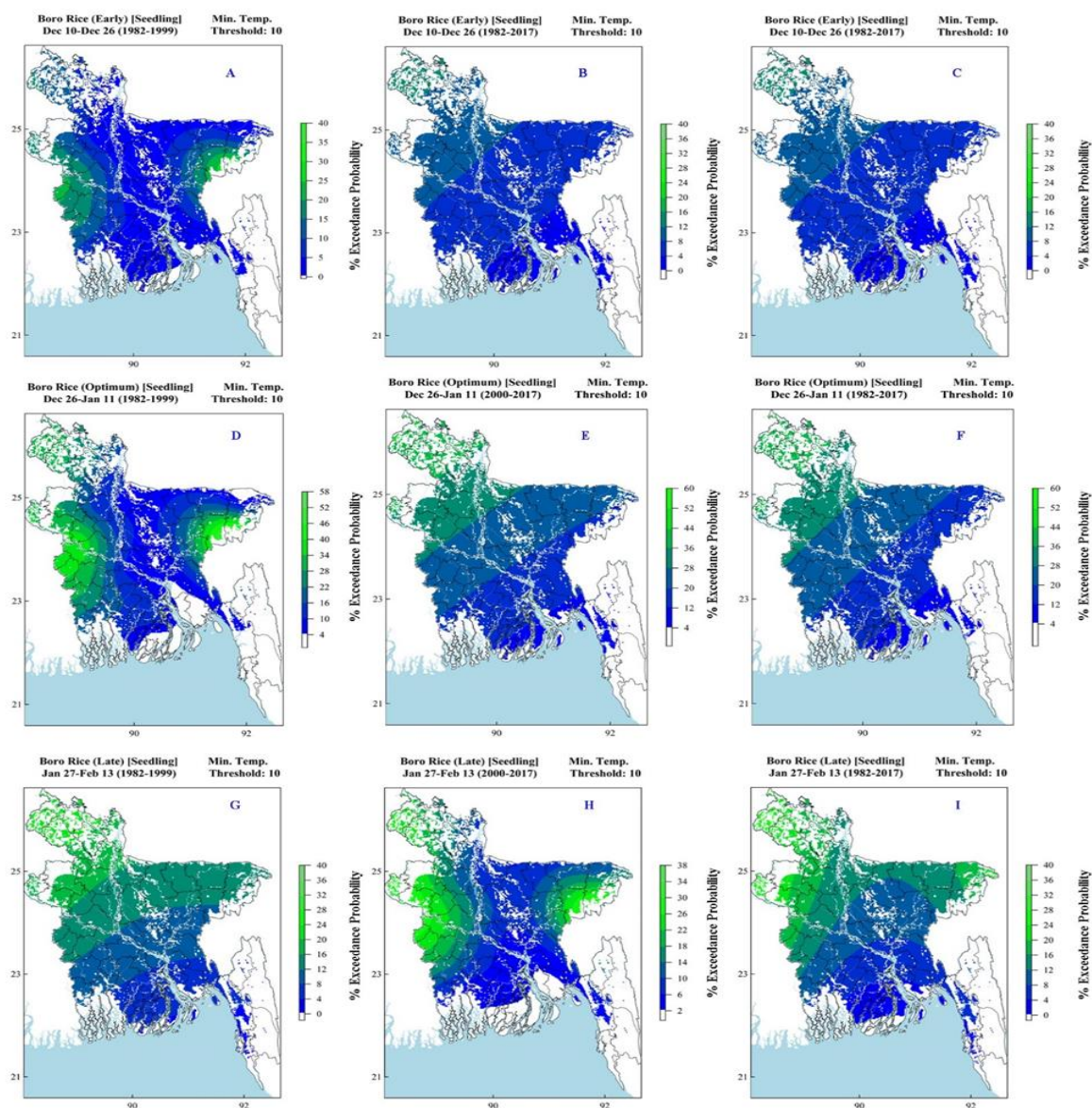


Figure 5. Exceedance probabilities for the low temperature threshold (10°C) during the seedling stage of boro rice were assessed for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) based on the time of sowing (early, optimal/recommended, and late)

When rice is sown during the optimal window of time, the crop is likely to enter the seedling stage between December 26 - January 11. Under this condition, the probability of exceeding the lower temperature threshold ranges 34-50% in some of the districts of Rangpur, Rajshahi, Sylhet and Khulna divisions. However, when considering recent and long-term climate periods, the chances of exceeding this threshold are remarkably higher (44-60%) than the historical climate, but only for all districts of Rangpur division and one district (Chapai Nawabganj) of Rajshahi division. With late sowing, the seedling stage is likely to begin between January 11-

27, irrespective of the climatic periods and locations. The probability of exceeding lower temperature threshold is 20-30% based on available data, regardless of climatic period, although observed patterns are different for the three climatic periods (Figure 6). The upper temperature threshold of rice at the seedling stage was identified at 35 °C, based on systematic literature review. As for sowing and germination stages, the cumulative distribution function probability maps for all three periods of climate data could not be generated for this threshold since temperatures above 35 °C during the seedling stage have never been observed in Bangladesh.



Above: Farmer is levelling his land after ploughing. Photo credit: Abdul Momin.

3.3.3 Maximum tillering

When rice is sown under early, optimum, or late conditions, expert consultation suggested that the crop will reach the maximum tillering stage somewhere between January 29-February 13, February 14-29, and March 16-April 1, respectively. The minimum and maximum temperature thresholds of rice at the maximum tillering stage were set at 10 °C and 35 °C, based on data collected from the systematic literature review. For *boro* rice sown early and irrespective of the climatic period considered, there is a 20-34% chance of exceeding the low-temperature threshold across all districts in Rangpur, Rajshahi and Sylhet divisions. If seeds are sown at the optimum time, maximum tillering during February 14-29, and the probability of cold temperature stress declines to 12-22%. Risk of low temperature stress also varies across the locations. On the other hand, late sowing generated no information since the probability of exceeding the lower-temperature threshold at the maximum tillering stage becomes negligible across all of Bangladesh (Figure 6).

Our analysis indicates that for seeds sown under early or late conditions, regardless of climate periods and locations, there is no chance of exceeding the upper-

temperature threshold at the maximum tillering stage. However, according to our expert consultation, if rice is sown late, the maximum tillering stage of *boro* rice may occur between March 16 and April 1. Based on historical climate data ranging from 1982-2017, the highest probabilities of exceedance (40-80%) of the upper temperature threshold were observed in several districts within the Rajshahi and Khulna divisions. Conversely, high-temperature threshold exceedance is only likely in Rajshahi, Natore, Pabna, Kushtia, Meherpur, Chuadanga, and Jhenidah. The probabilities range from 37-47% with recent climate data and 40-50% with long-term data (Figure 7).

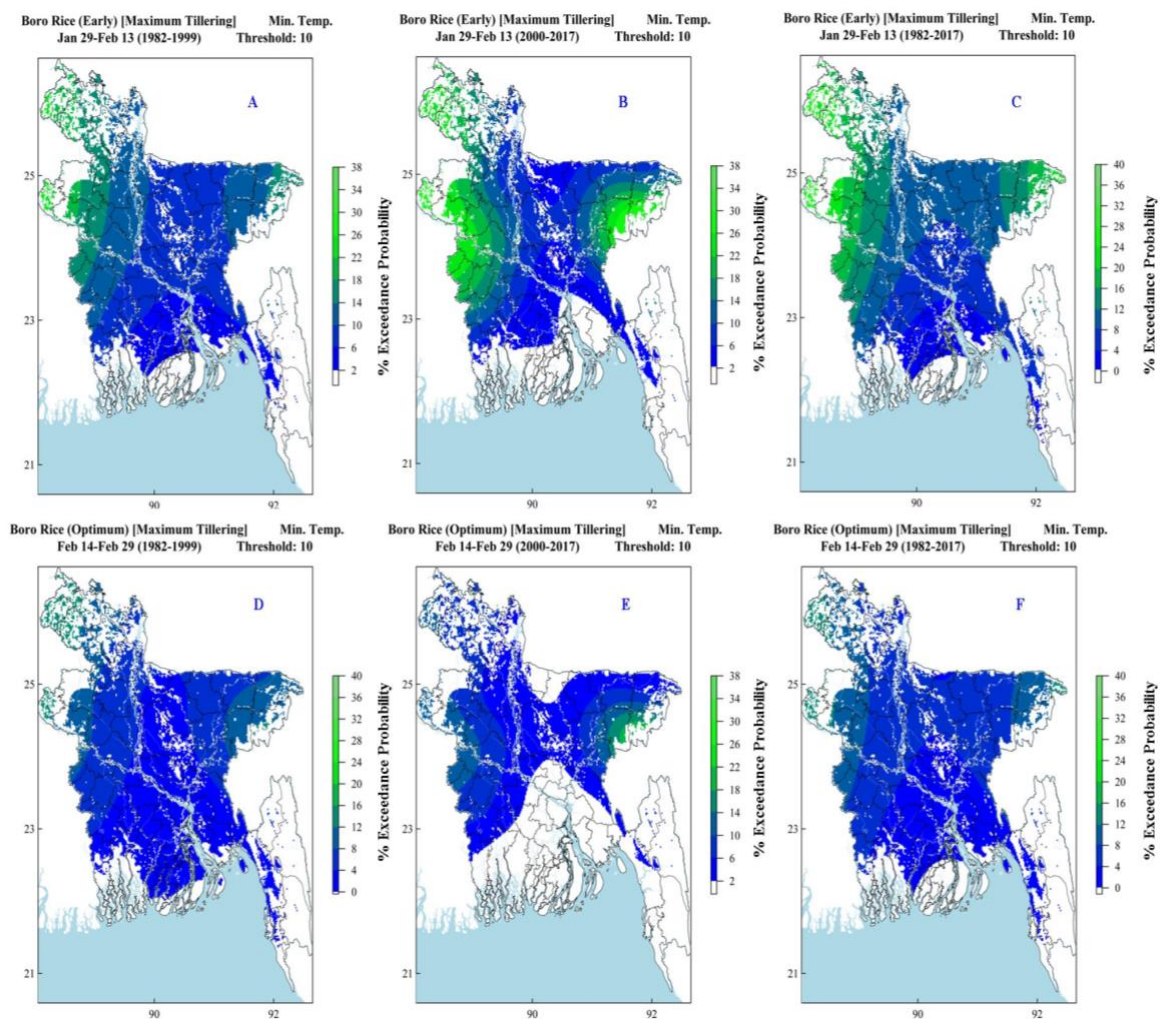


Figure 6. Exceedance probabilities were calculated for the low temperature threshold (10 °C) at the maximum tillering stage of boro rice for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), considering early, optimal, and late sowing times.

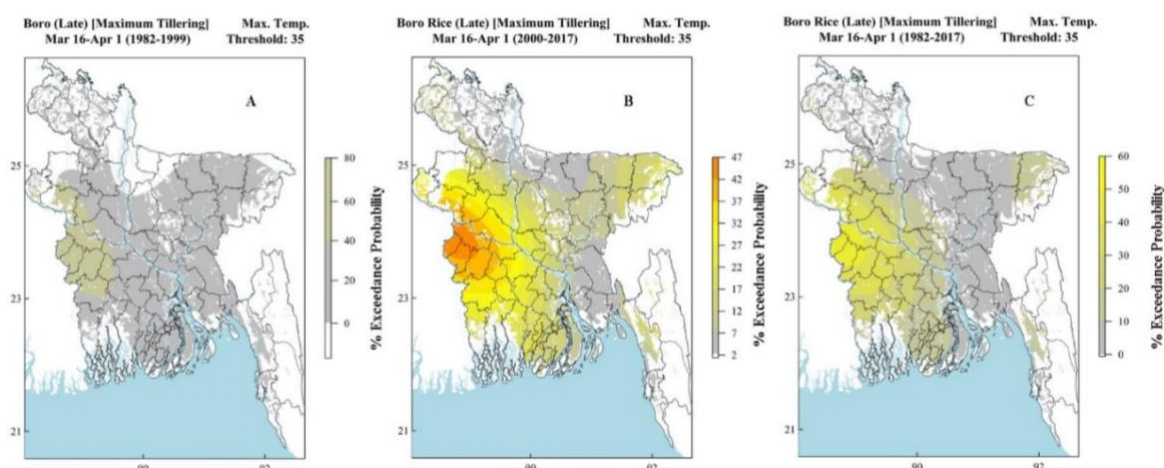


Figure 7. Exceedance probabilities for the high temperature threshold (35 °C) at maximum tillering stage of boro rice for the from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

3.3.4 Heading and flowering

Our expert consultations suggest that rice sown under early, optimum, or late conditions could reach the heading and flowering stages between February 28 and March 13, March 14 and 27, and April 10 and 25, respectively. Based on our systematic literature review, the lower and upper temperature thresholds for *boro* rice at the heading and flowering stages were identified as 17 °C and 35 °C, respectively. When seeds are sown early, using historical climate data for probability modelling, the chances of exceeding the low temperature threshold at this stage in Rangpur division range from 60 to 100%. In Rajshahi, most parts of Mymensingh, and in Sylhet divisions, there is a 60-80% chance of exceeding the low temperature threshold. However, with recent and long-term climates, there is a 40-90% probability of exceedance following the same pattern, but with slightly higher probabilities for recent climate data. Low temperature stress is also a concern in the north-western, southern, and north-eastern parts of the country. For *boro* rice sown at the optimum time, the chances of cold stress thresholds at heading and flowering ranged from 32 to 50%, 46 to 78%, and 43 to 55% for the three climatic periods. The most affected areas were observed in the western, north-western, and north-eastern parts of the country. The low temperature vulnerability of late-sown *boro* at heading and flowering is lower than for the early or optimum sowing, ranging from 4.6 to 7.8%, 20 to 36%, and 14 to 20% for the three climate periods studied, respectively (Figure 8)

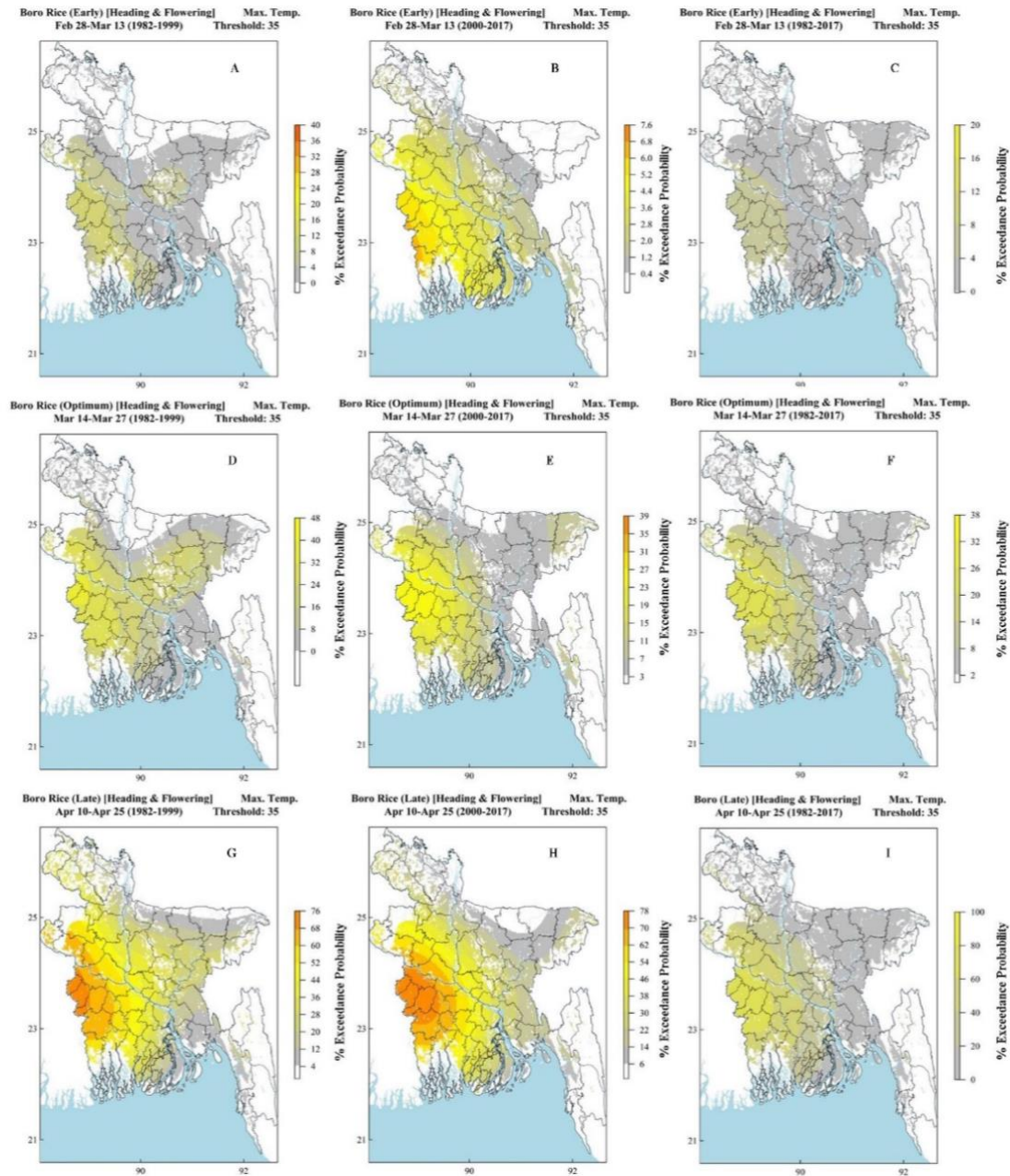


Figure 8. Exceedance probabilities for the low temperature threshold (17°C) during the heading and flowering stage of boro rice were calculated for the climatic periods of 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) considering three different planting times: early, at the recommended or optimal dates, and late.

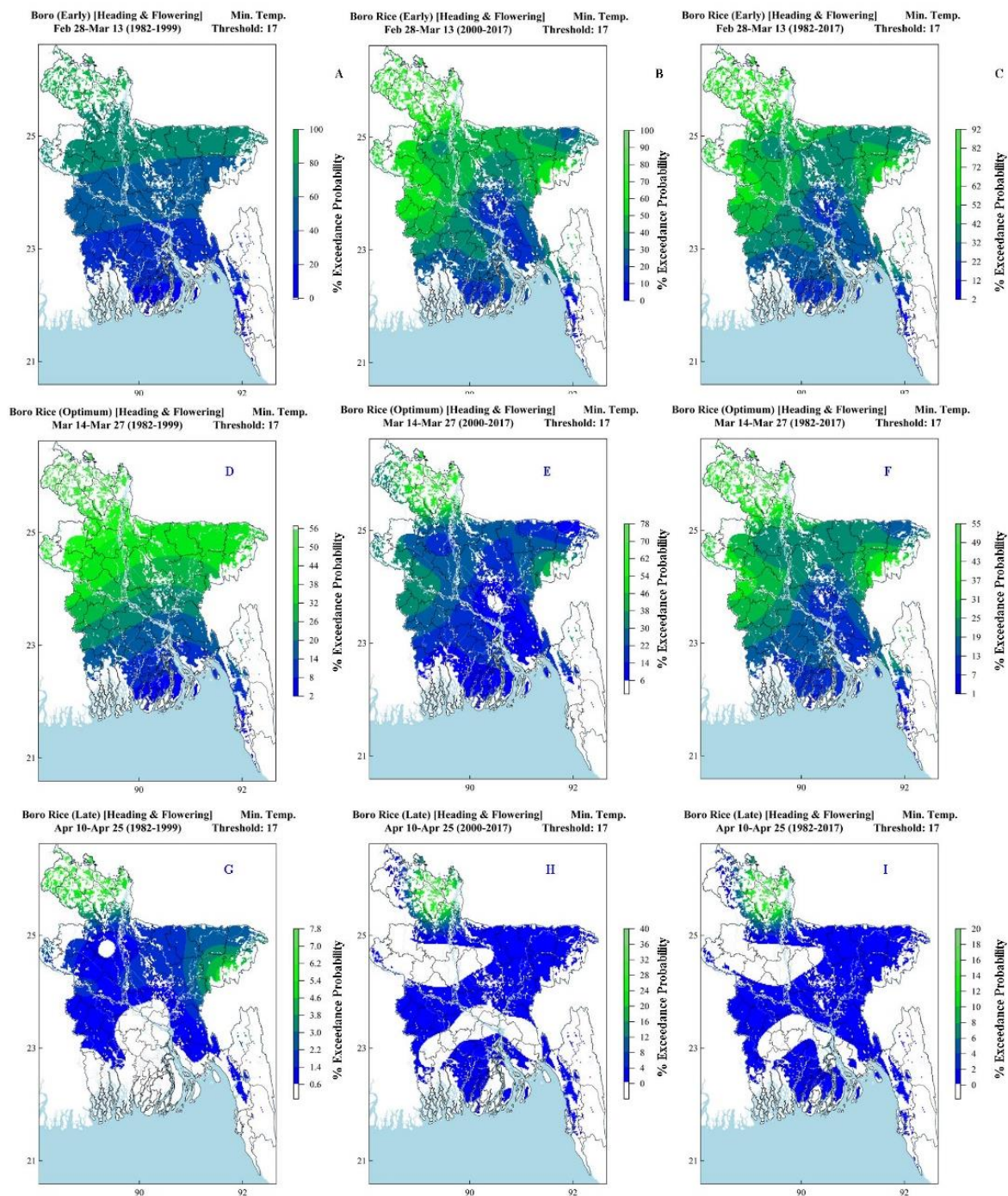


Figure 9. Exceedance probabilities for the high temperature threshold (35 °C) at the heading and flowering stage of boro rice for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late.

For all climatic periods, the probability of exceeding the upper-temperature threshold at the heading and flowering stage for early-sown *boro* rice is low, ranging from 4-8%, 5.2-6.8%, and 8-12%, respectively. Geographically, heat stress

could be an issue in Khulna, Rajshahi, and Barisal divisions. For optimum and late-sown *boro* rice, the pattern of threshold exceedance is similar, but the probability is higher for optimum sowing (20-26%, 23-31%, and 32-40% for the three periods, respectively). During our research, expert input suggested that late-sown winter season rice is more likely to flower late in the season. Therefore, the probability of exceeding high-temperature thresholds, which could lead to heat stress, is higher

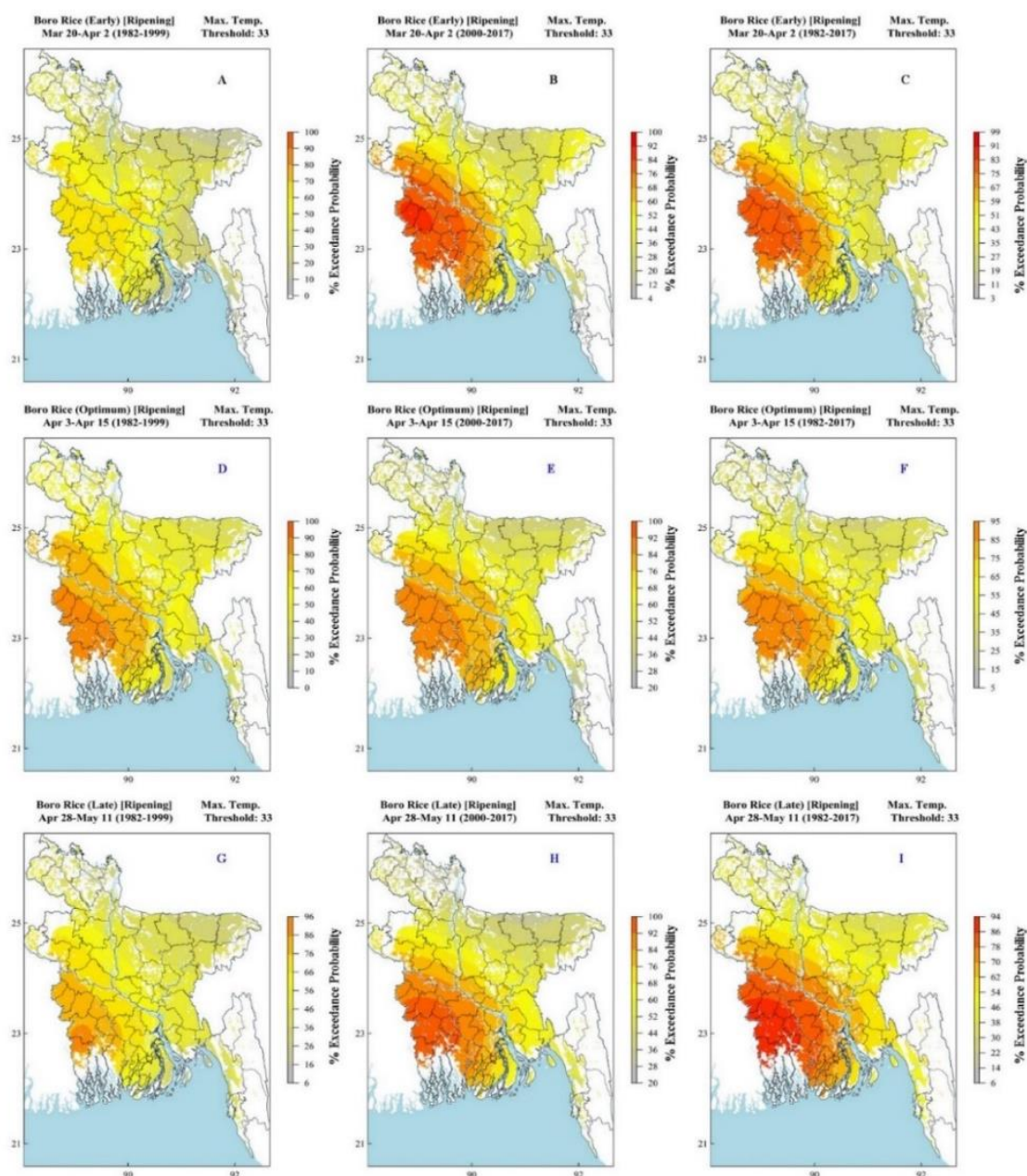


Figure 10. Exceedance probabilities were calculated for the high temperature threshold (33 °C) at the ripening stage of boro rice for the climactic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), considering the planting times of early, optimal or recommended dates, and late.

(60-76%, 62-78%, and 60-80% using observed temperature data from 1982-1999, 2000-2017, and 1982-2017, respectively).

3.3.5 Ripening

During our research, expert consultations suggested that winter season rice sown under early, optimum, or late conditions could reach the ripening stage between March 20-April 2, April 3-15, and April 28-11 May, respectively. Based on our literature review, we identified the lower and upper temperature thresholds for rice at this stage as 13 °C and 33 °C, respectively. We found that there is no chance of exceeding the lower-temperature threshold at the ripening stage in some parts of Bangladesh, so no maps were generated regardless of planting times or climate periods. However, there is a clear risk of exceeding the upper-temperature thresholds. For early sowing, the probabilities of exceeding the upper-temperature threshold during the ripening stage range from 50-70%, 60-100%, and 59-83% for the three climate periods, respectively, with hotspots located in the southwestern and western districts. Similar patterns were observed for optimum and late sowing, although with higher probabilities of exceedance in the southwestern and western districts. The percentages of exceedance for the three climatic periods were 70-90%, 76-92%, and 75-95% for optimum sowing, and 76-96%, 76-100%, and 70-90%, 76-92%, and 75-95% for optimum sowing, and 76-95%, 76-100% and 70-94% for late sowing (Figure 10).

3.4 Thermal thresholds exceedance for various critical development stages of aus rice

3.4.1 Sowing and germination

The temperature thresholds for rice at sowing and germination were found to be 10 °C and 35 °C, respectively. Our research indicates that there is no risk of crop damage due to low temperatures when aus rice is sown between March 20 and April 25, regardless of sowing time or climate period. However, there is a minimal risk of exceeding the low-temperature threshold if the crops are sown early or at the optimum time. Late-sown crops have a higher probability of exceeding the threshold, ranging from 9-15%, 4-8%, and 3-5% for the three climate periods studied. Geographically, these higher probabilities of exceedance are concentrated in a few districts of Rajshahi and Khulna divisions when using historical climate data. The geographical concentrations of higher probabilities of exceedance with the historical climate data were for only a few districts of Rajshahi and Khulna divisions. In the recent climate dataset, the probabilities of exceeding the lower temperature threshold for aus rice were also concentrated in Rajshahi and Khulna divisions. However, the number of districts affected was higher than in the historical climate. In the long-term climate, the concentrations were mostly observed in Rajshahi, Chapainawabganj, Kushtia, Meherpur, and Chauadanga districts (Figure 11).

3.4.2 Seedling stage

Our systematic literature review identified the lower and upper temperature thresholds for *aus* rice at the seedling stage as 10 °C and 35 °C, respectively (Table 2). Based on expert consultations, *aus* rice sown under early (20-29 March), optimum (29 March-7 April), or late (16-25 April) conditions are likely to germinate

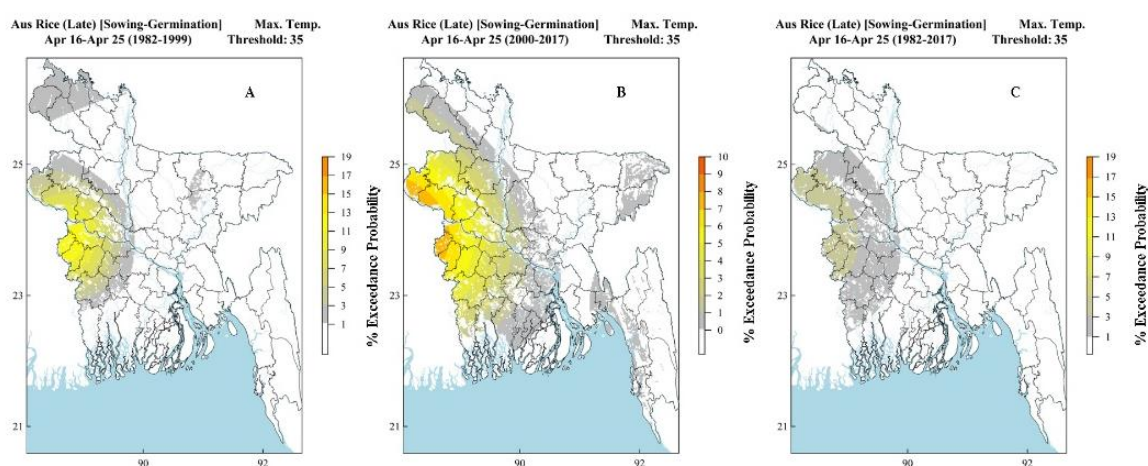


Figure 11. The exceedance probability for upper temperature threshold (35 °C) at sowing and germination stage of *aus* rice when sown late for climatic period 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), respectively. The probabilities were analysed for late sowing. Note that maps were not generated for simulations that returned only zero probability values.

and enter the seedling stage between 11-20 April, 20-29 April, and 8-17 May, respectively. During this period, there is no chance of crop damage due to cold stress, irrespective of the climate period studied. However, the probability of heat stress at this stage following early sowing is high, ranging from 44-68%, 54-78%, and 40-100%, respectively, for the three climatic periods.

The spatial distribution of exceedance of lower temperature thresholds with higher probabilities for historical and recent climatic periods was spread over the districts of Rajshahi and Khulna divisions, whereas for the long-term climate, they mainly concentrated in Khulna division. The distribution for the upper temperature threshold examined during optimum sowing dates was similar, with probabilities ranging from 52-76%, 46-78%, and 60-100%, respectively, for the three climate periods. For the late-sown rice, probabilities were 60-100%, 42-66%, and 50-70%, respectively, for the three climatic periods. Higher probabilities occurred predominantly within Khulna division (Figure 12).

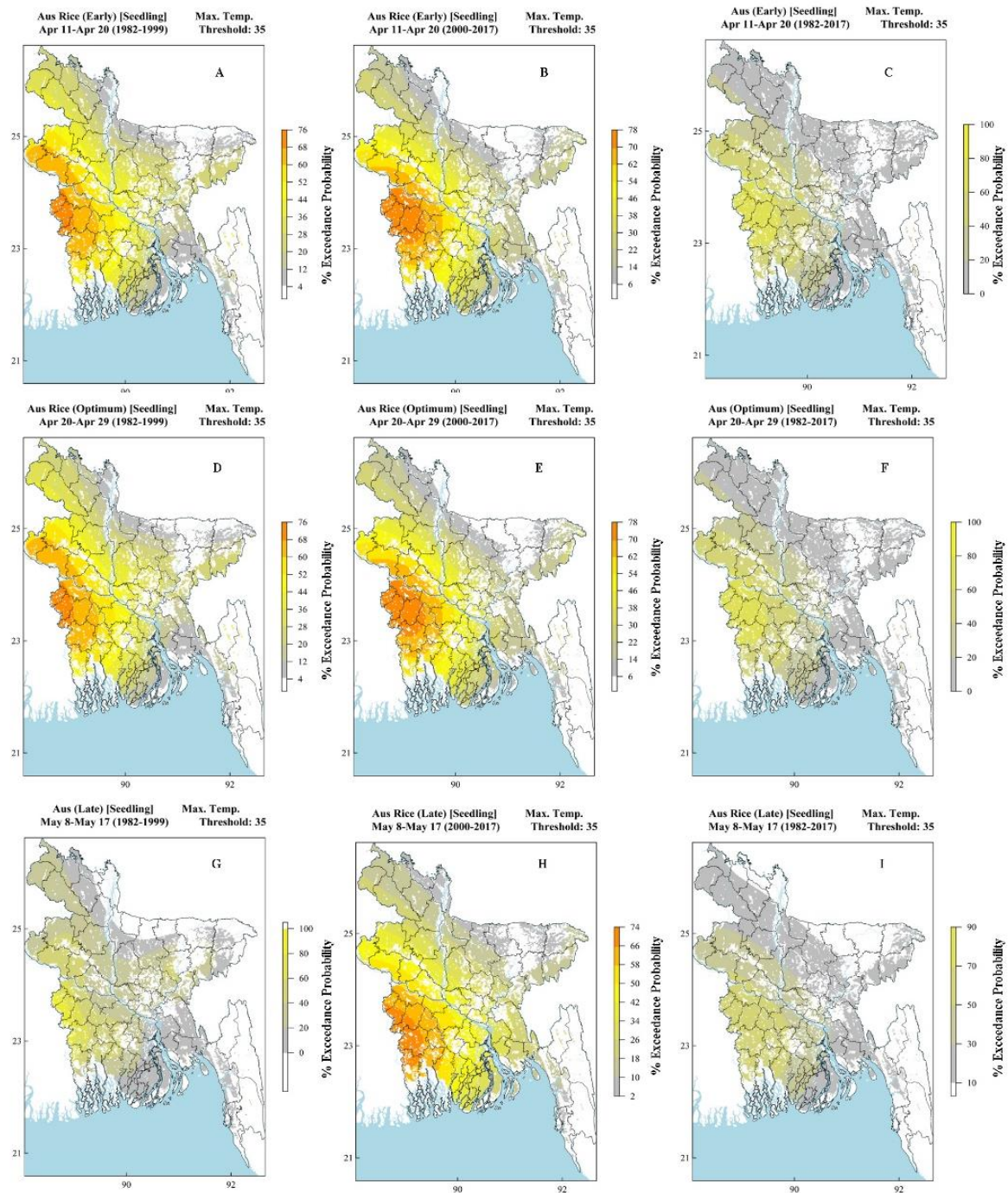


Figure 12. Exceedance probabilities for the upper temperature threshold (35 °C) at the seedling stage of aus rice was calculated for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) for different planting times: early, optimal/recommended, and late.

3.4.3 Maximum tillering

Based on our systematic literature review, we identified the lower and upper temperature thresholds for *aus* rice at maximum tillering to be 14°C and 35°C,

respectively. Our expert consultations indicated that the maximum tillering stage for early, optimum, and late sown farmers is likely to occur between 23-30 May, 30 May-7 June, and 15-23 June, respectively. No cold stress was observed during this period. However, even early established rice has a high risk of encountering heat stress (40-100%, 42-74%, and 50-70%, respectively for the three climatic periods) (see Figure 13), with Khulna, Barisal, and parts of Rajshahi division being at a higher risk compared to other locations. More optimally established rice still has a risk of 40-80% of encountering heat stress, regardless of the climate period studied. The same pattern was observed for late-sown rice, with 28-46%, 40-60%, and 60-80% risks for the historical (1982-1999), recent (2000-2017), and long-term (1982-2017) climate periods, respectively. These risks were mainly concentrated in Khulna and Rajshahi divisions.



Above: Farmer preparing land using two-wheel tractor power tiller in Bangladesh. Photo Credit: Abdul Momin.

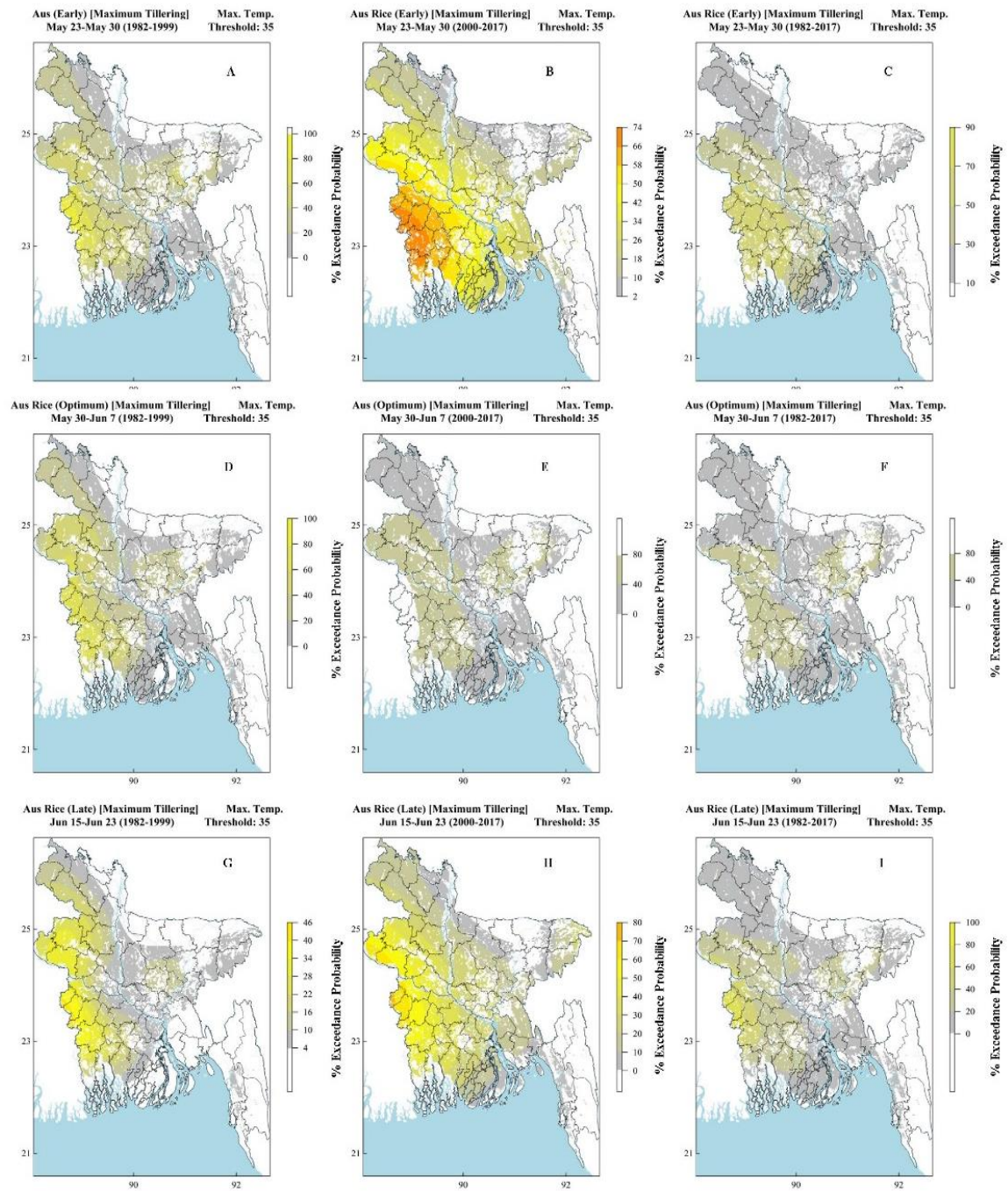


Figure 13. Exceedance probabilities for the upper temperature threshold (35 °C) at the maximum tillering stage of aus rice were calculated for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when the crop was sown early, at optimal or recommended dates, and when sown late.

3.4.4 Heading and flowering

The lower and upper temperature thresholds for *aus* rice during the heading and flowering stage are 17 °C and 35 °C, respectively. Regardless of the climatic periods and locations, when *aus* rice was sown under early, optimum, or late conditions, the crop reached the heading and flowering stage between 17-24 June, 24 June-2 July, and 9-17 July, respectively. During this time, temperatures are very high in Bangladesh, so there is no chance of *aus* rice suffering from low temperature stresses. Therefore, no maps were generated for the probabilities of exceedance of lower temperature thresholds for any climatic periods or sowing times. However, mapping exceedance probabilities for the upper temperature threshold showed a clear pattern across locations or climatic periods (figure 14)



Above: Farmers in Bangladesh using traditional water lifting techniques to irrigate their crops. Photo Credit: Abdul Momin.

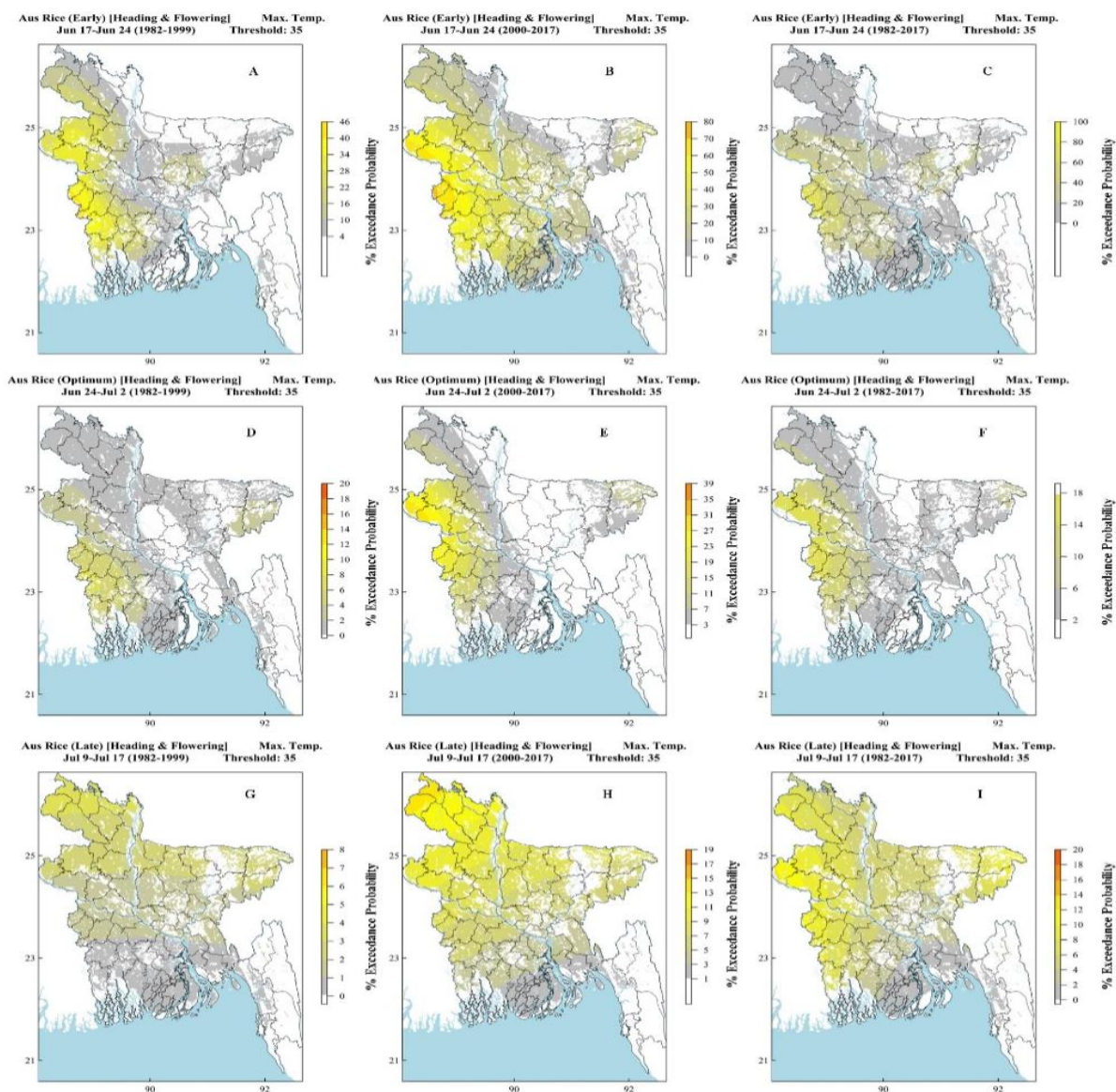


Figure 14. Exceedance probabilities have been calculated for the upper temperature threshold (35° C) during the heading and flowering stage of aus rice. These probabilities are based on data from the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), and take into account different sowing times: early, at the optimal or recommended dates, and late.

3.4.5 Ripening

The systematic literature review identified the lower and upper temperature thresholds for rice at the ripening stage as 13°C and 33°C, respectively. Assuming *aus* rice was sown early, optimally, or late, the ripening stage was expected to occur between 3-9 July, 9-16 July, and 23-30 July, respectively, with no risk of cold stress

during this period. However, there was a high probability of exceedance of the upper temperature threshold, and thus maps were generated for all sowing times and climatic periods (Figure 15).

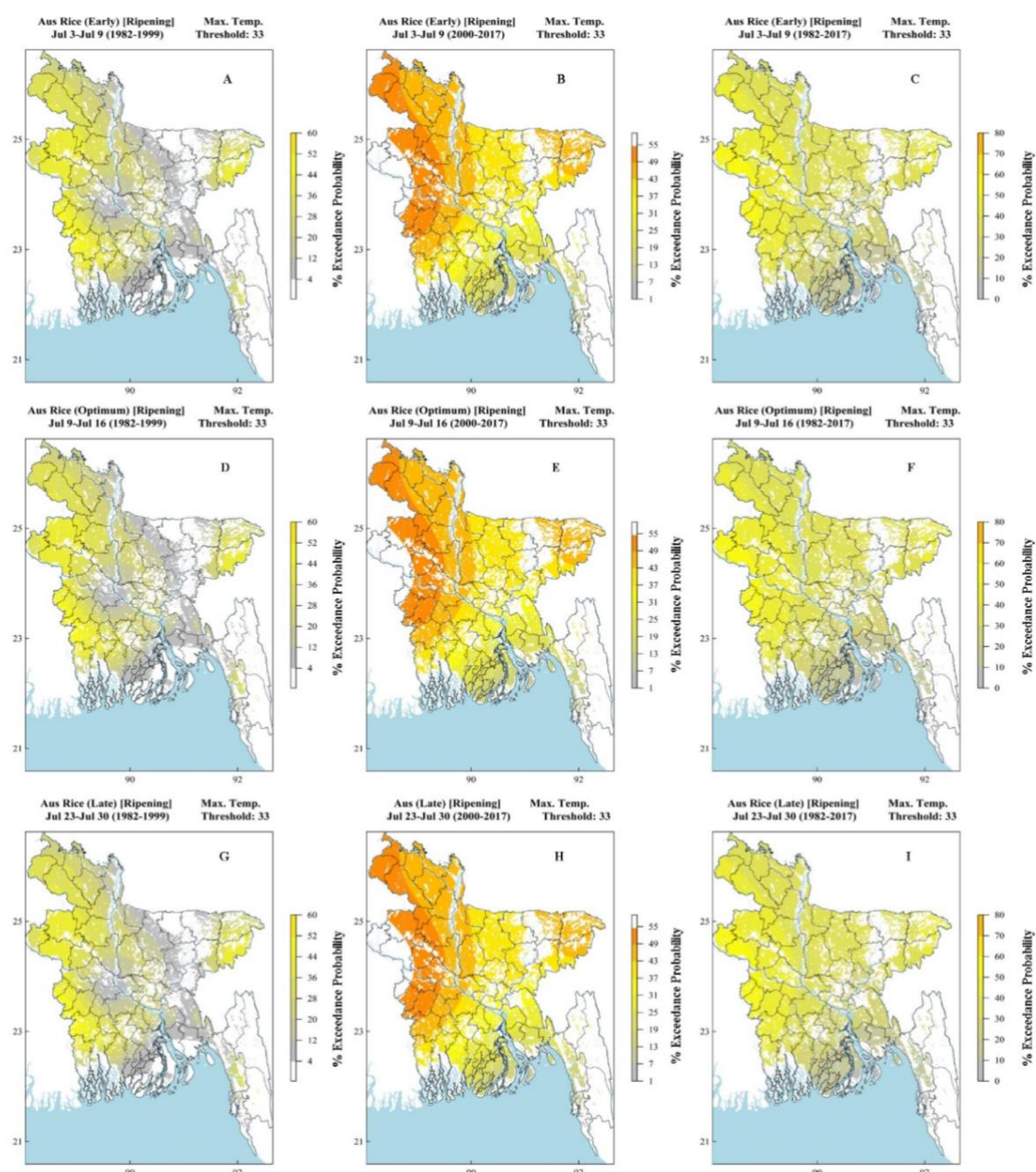


Figure 15. Exceedance probabilities for the upper temperature threshold (33°C) during the ripening stage of aus rice are provided for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) for early, optimal or recommended, and late sowing times.

Exceedance probabilities for the upper temperature threshold ranged from 36-60% for early, 31-55% for optimum, and 30-70% for late-sown crops, respectively, for the three climatic periods. For the long-term historical climate data, hotspots were identified in the south-west, west, north-west, and in Sylhet and Moulvibazar districts in northeast Bangladesh. For the recent climate period considered, higher probabilities of occurrence were found in 8, 6, 6, and 3 districts of Rangpur, Rajshahi, Khulna, and Sylhet divisions, respectively. Areas at risk of high-temperature stress were also observed in some parts of Jamalpur, Tangail, Manikganj, Rajbari, and Faridpur districts. The distribution of higher probabilities with long-term climatic data was similar to the historical climatic data.

On the other hand, threshold exceedance probabilities were lower for late-sown *aus* rice, ranging from 3-7%, 7-15%, and 6-14% for the three climate periods, respectively. This is due to the ripening stage coinciding with reduced temperatures as the early monsoon commences.

3.5 Thermal thresholds exceedance for various critical development stages of aman rice

3.5.1 Sowing and germination

Our systematic literature review revealed that the lower and upper temperature thresholds for *aman* rice during sowing and germination are 10 °C and 35 °C, respectively, as shown in Table 2. It's important to note that rice sown between June 20 and July 31 is less likely to experience cold or heat stress. Hence, regardless of sowing time or climate period, the CDF maps for all three periods of climate data could not be generated for these thresholds.

3.5.2 Seedling stage

The lower and upper temperature thresholds for *aman* rice at the seedling stage have been established as 10 °C and 35 °C, respectively. Regardless of the climatic periods and locations, when *aman* rice was sown under early (June 20-July 2), optimum (July 3-14), or late (July 26 – 31) conditions, the crop reached the seedling stage between July 17-29, July 29-August 10, and August 22-September 3, respectively. As the lower temperature threshold was not exceeded, there was no risk of crop damage during this stage, and thus, CDF maps could not be generated. However, for the upper-temperature threshold, the probabilities of exceedance for early sowing were found to be 3-5%, 9-15%, and 10-12% for historical, recent, and long-term climatic periods, respectively.

In terms of geographical distribution, districts with higher probabilities of exceedance for the historical climate period were Thakurgaon, Panchogarh, Nilphamari, and Lalmonirhat in the Rangpur division. For the recent climatic period, they were Nagaon, Jaypurhat, Chapainawabganj, and Rajshahi districts in Rajshahi division, all the districts in Rangpur division, and Jashore, Kustia, and Meherpur in Khulna division. For the long-term climatic period, higher probabilities of exceedance of the upper temperature threshold were found in Panchgarh district of Rangpur division, Nagaon,

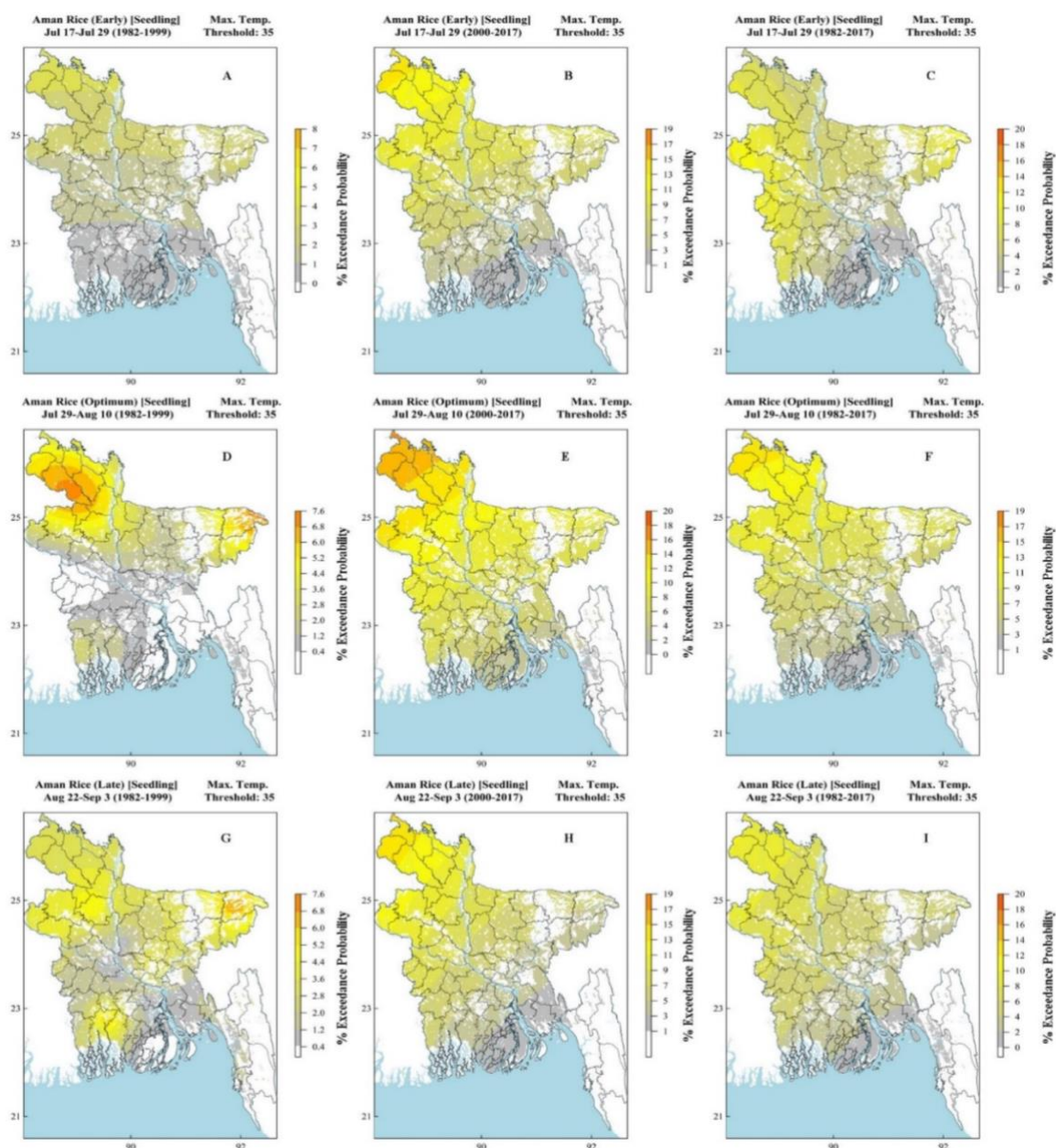


Figure 16. Exceedance probabilities were calculated for the upper temperature threshold (35°C) during the seedling stage of aman rice. The analysis was conducted for the periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), taking into account different sowing times: early, at optimum or recommended dates, and late.

Jaypurhat, and Chapainawabganj districts of Rajshahi division, Jashore, Kushtia, Meherpur, and Chauadanga districts of Khulna division, as well as Sylhet and Moulvibazar districts of Sylhet division (Figure 16) When *aman* rice is sown during the optimum and recommended time (i.e., 2-14 July), probabilities of upper temperature threshold exceedance were 4.4-7.6, 10-20 and 11-15% respectively for the 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) climatic periods. The higher values of exceedance the 1982-1999 period observed for Dinajpur, Rangpur, Thakurgaon, Panchogarh, Nilphamari, Gaibandha and

Lalmonirhat districts of Rangpur division, Nagaon, Jaypurhat and Bogura districts of Rajshahi division, and Sylhet and Moulavibazar districts of Sylhet division. For the recent (2000-2017) and long-term climatic periods, the distribution pattern was similar, with higher values occurring predominantly in the western and north-western parts of the country. For the late-sown rice (i.e., 26-31 July), the spatial distribution was similar to the long-term climate period (Figure 16).

3.5.3 Maximum tillering

Based on a systematic literature review, the lower and upper temperature thresholds for rice at the maximum tillering stage were found to be 14°C and 35°C, respectively. Expert consultations identified the maximum tillering stage for summer *aman* rice to occur between 11-21 September, 21 September – 1 October, and 22 11-21 October, respectively. The probabilities of exceedance of higher temperature thresholds across these sowing times varied between 2.4-8.0%, 4.6-20.0%, and 4.0-1% for the three climate periods studied, respectively. Slightly lower probabilities were observed for late-sown rice, and these probabilities were concentrated mostly in the north-western and northern parts of the country (Figure 17).



Above: Farmer ploughing his land using traditional method in Bangladesh. Photo Credit: Abdul Momin.

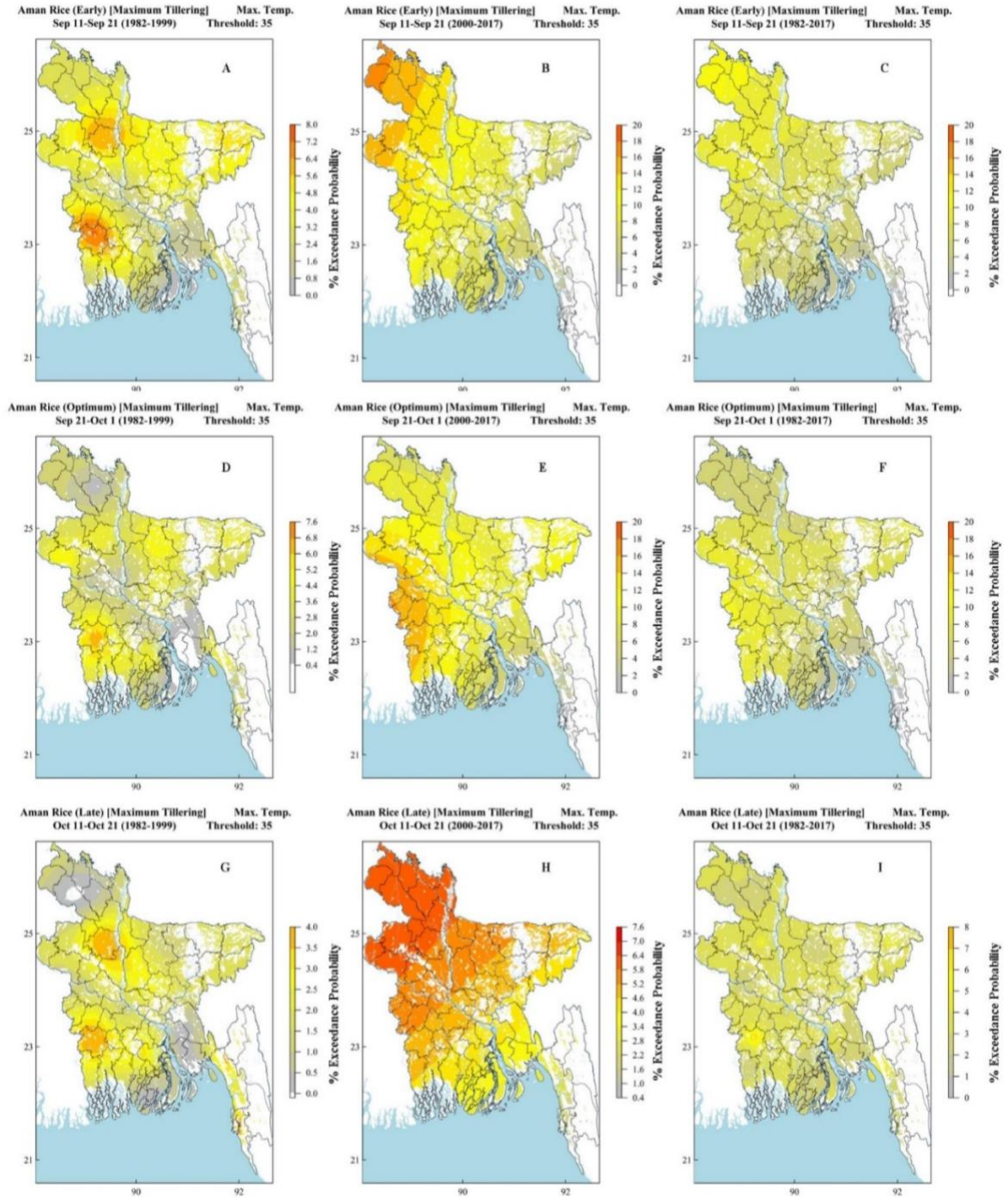


Figure 17. Exceedance probabilities for the upper temperature threshold (35°C) at the maximum tillering stage of aman rice were calculated for the periods of 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), considering different sowing times, including early, optimal or recommended, and late.

3.5.4 Heading and flowering

The lower and upper temperature thresholds for *rice* heading and flowering were identified as being 17 °C and 35 °C, respectively (Table 1). When summer rice is sown at the early or at optimum time, our data suggest that there was very little chance of cold crop damage. However, when the crop was sown late, risk was more pronounced and tended to follow a diagonal southwest-northeast pattern with the gradation of high to low percentages from north to south. Lower temperature exceedance probabilities at heading and flowering from November 5 to 15 ranged from 46-78%, 43-55%, and 54-78% for the three climate periods studied (Figure 18).

Our analysis suggested that heat stress could be a risk heading and flowering from June 17 and 24, at a probability of 2.5-4.0%, 4.0-7.6%, and 4-6% for the 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) climate periods, respectively. Similar results were obtained for rice sown at the optimum time for these periods (Figure 19).

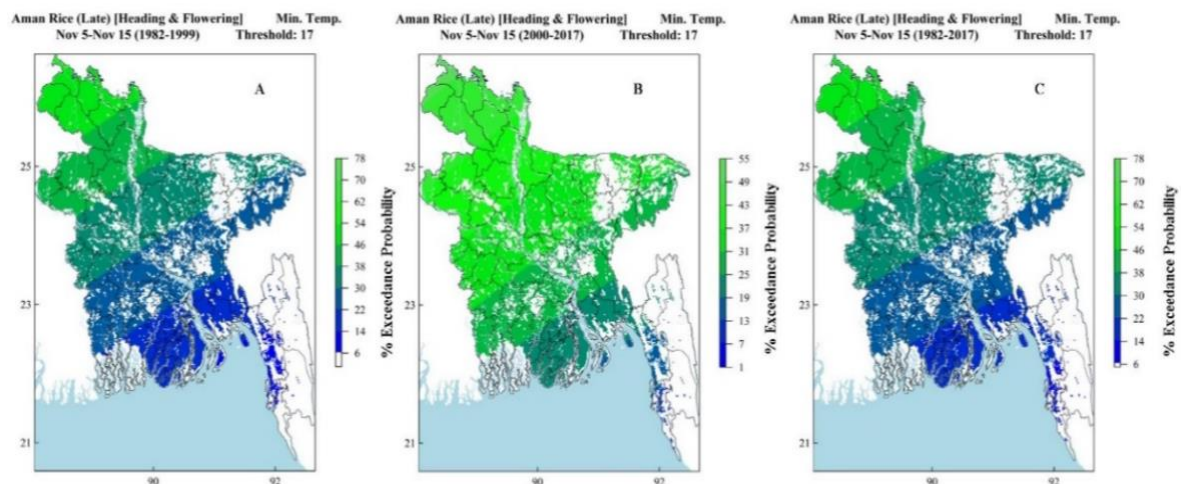


Figure 18. Exceedance probabilities for the low temperature threshold (17°C) during the heading and flowering stages of aman rice were calculated for the periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), taking into account early, optimal or recommended, and late sowing times. Note that maps were not generated for simulations that returned only zero probability values.

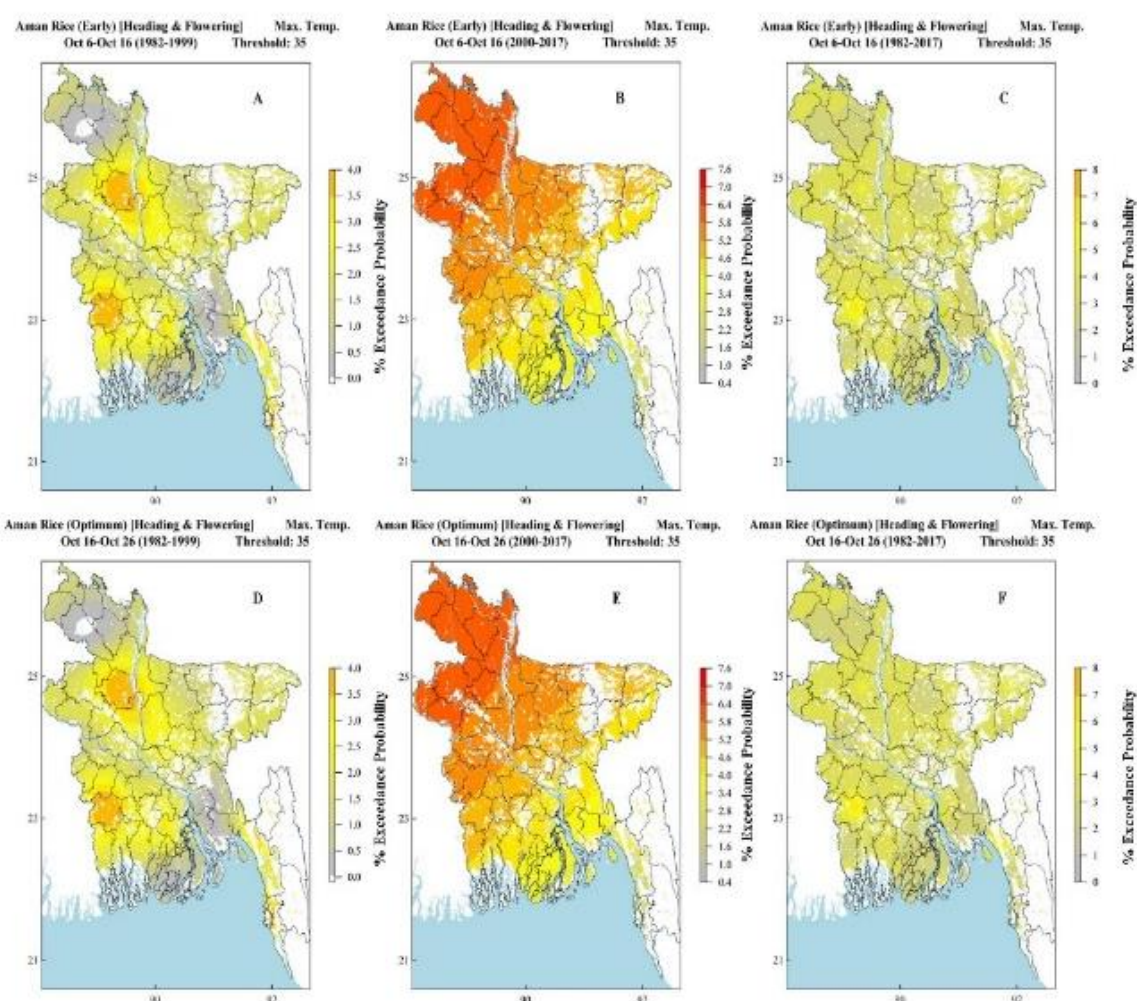


Figure 19. Exceedance probabilities for high temperatures (35°C) during the heading and flowering stages of aman rice were assessed for different sowing times, including early, optimal/recommended, and late, over the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term). Note that maps were not generated for simulations that returned only zero probability values.

3.5.5 Ripening

Based on a systematic literature review (Table 2), the lower and upper temperature thresholds for rice were found to be 13 °C and 33 °C, respectively. The ripening period for summer *aman* rice was estimated to be between 22 October-1 November, 1-11 November, and 21 November-1 December, respectively, based on structured expert consultation workshops conducted during the research. For early sowing, the probability of exceeding the lower temperature threshold was found to be negligible in all districts and for all climate periods, which prevented the generation of probability exceedance maps. However, slight chances of exceeding the low temperature threshold were found for rice sown during the

recommended dates (2.3-4.7%, 3.0-8.0% and 2.6-5.6%, respectively, for the three climatic periods studied). Probabilities of exceeding the low temperature threshold increased for late-sown rice (7-11%, 12-32%, and 10-18%), with most risk identified in the western, north-western, and north-eastern parts of the country (Figure 20)

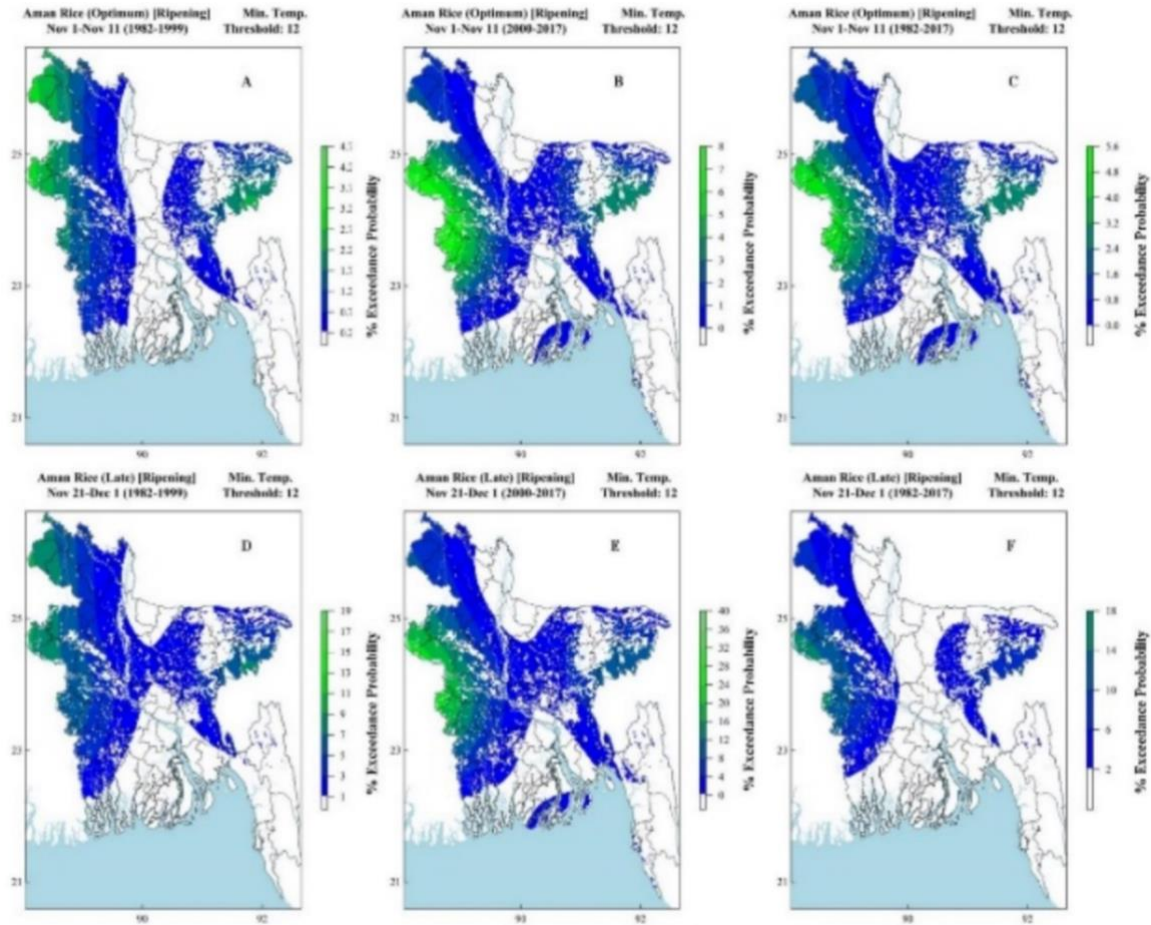


Figure 20. Exceedance probabilities for the lower temperature threshold (12°C) during the ripening stage of aman rice were analysed for the periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when the crop was sown early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

The probabilities of exceeding the upper temperature threshold (33°C) for early sown *aman* rice were found to be relatively high (20-28%, 8-14%, and 12-16%) for the three climate periods studied. Heat stress risk was identified for *aman* rice areas across the entire country. Similarly, a comparable pattern was observed for optimum planting, but with lower probabilities of exceedance (2.4-3.2%, 4.0-6.0%, and 2.0-4.0%) across the three climate periods (Figure 21).

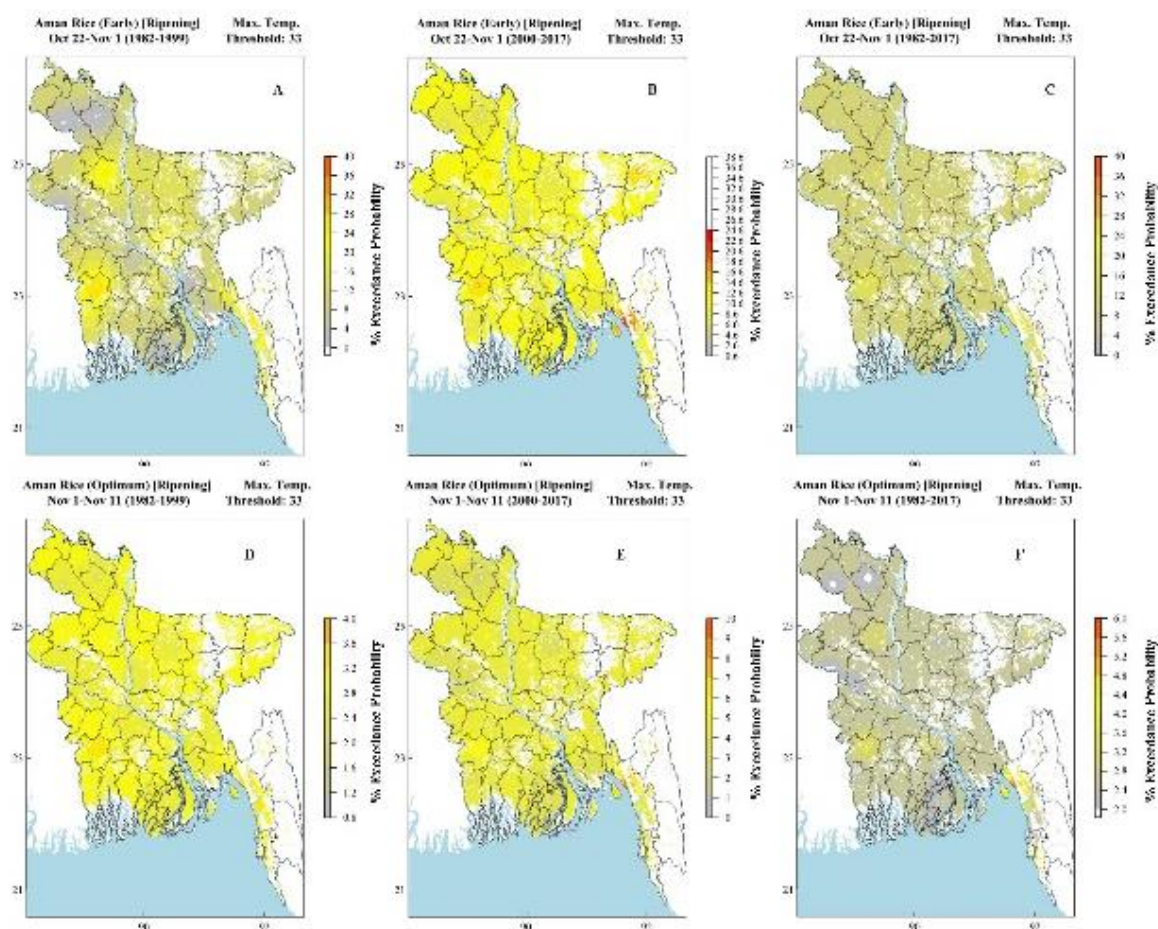


Figure 21. The exceedance probabilities for the upper temperature threshold (33°C) at the ripening stage of aman rice were evaluated for the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), when sown early, at optimal or recommended dates, and when sown late. It should be noted that maps were not generated for simulations that resulted in zero probability values.

3.6 Thermal thresholds exceedance for various critical development stages for wheat

3.6.1 Sowing and germination stage

Based on a systematic literature review, the lower and upper temperature thresholds for the sowing and germination stage of wheat were determined to be 3 °C and 33 °C, respectively. In Bangladesh, the risk of cold stress is negligible for wheat sown between November 1 and December 30 since temperatures rarely drop below the lower threshold. However, there is a slight probability (ranging from 2.8% to 6%) of exceeding the upper temperature threshold during the early and optimum sowing periods (November 1-30), depending on the climate period. This probability has been observed in scattered locations across the country, including Thakurgaon, Panchogarh, Kurigram, Jaypurhat, and Chapainababganj in the northwest, as well as Meherpur, Kustia, Chauadanga, and beyond the upper threshold, regardless of the climate period from which Jasore in the southwest,

and Chattogram district in the southeast. Late-sown wheat (December 15-30) is unlikely to experience high temperatures data were analysed (Figure 22).

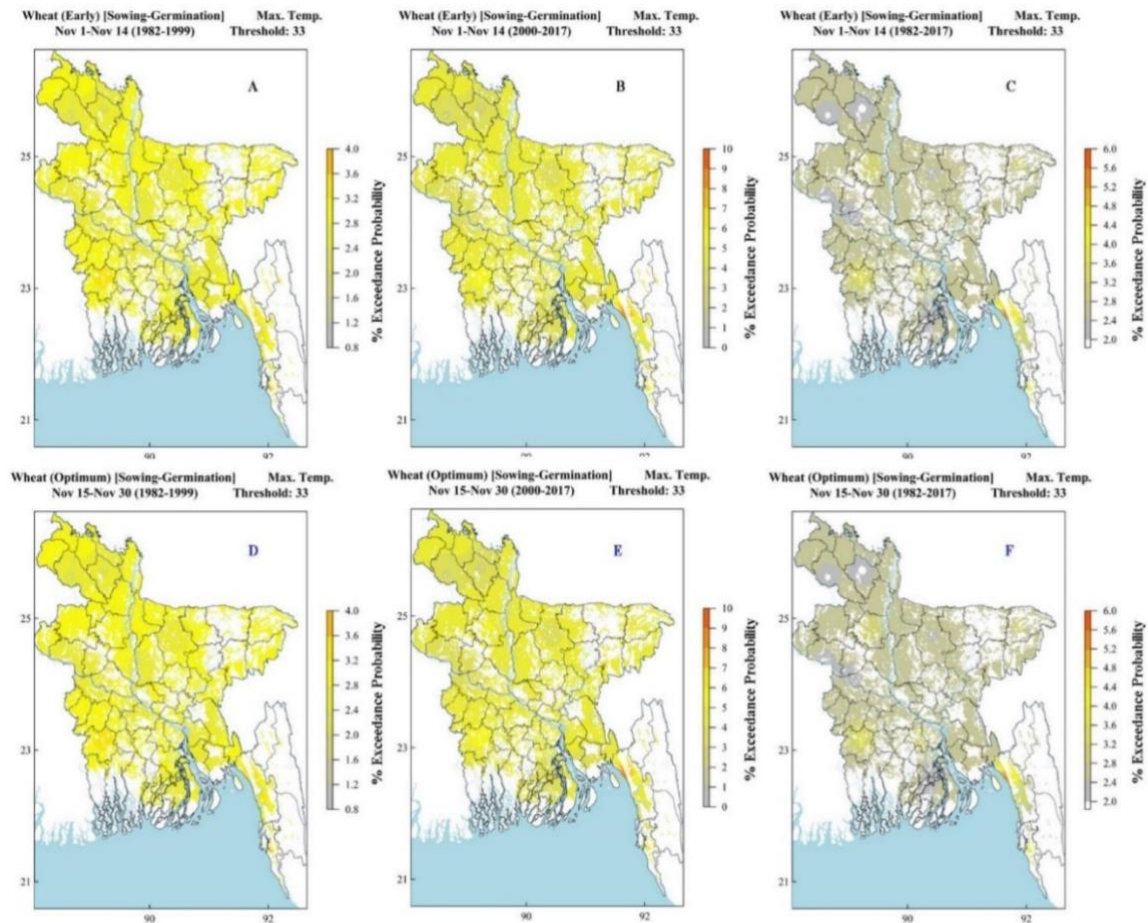


Figure 22. Exceedance probabilities for the upper temperature threshold (33° C) at the germination stage of wheat from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

3.6.2 Vegetative stage

The lower and upper temperature thresholds for the vegetative stage of wheat were identified as 6.4 °C and 30 °C, respectively, based on our systematic literature review. Wheat typically reaches the vegetative stage between December 6-20 (early sowing), December 16-29 (optimum sowing), and January 5-18 (late sowing), as suggested by experts. For early-sown wheat, the probability of falling below the lower temperature threshold during the vegetative stage is minimal, regardless of the climate period. However, for optimum sowing and historical climate periods, there is a slight probability (1.2-2.0%) of such threshold exceedance in some districts

of Rajshahi, Khulna, Rangpur, and Sylhet divisions. Similarly low probabilities of threshold exceedance (1.1-4%) were also observed for recent and long-term climate periods, particularly in Nilphamari, Kurigram, Rangpur, Lalmonirhat, and Moulvibazar and Hobiganj districts.

If wheat is sown late and the historical climate period data is considered, there is a higher probability (15-20%) of falling below the lower temperature threshold in Moulvibazar and Hobiganj districts in the northeast, and 10-15% in the northwest, southwest, and Netrokona and Kishoreganj districts. For recent climate data (2000-2017), there is a 5-7% chance of threshold exceedance, particularly in Moulvibazar and Hobiganj districts, and a 3-5% chance in other districts. For long-term climate data, the probabilities of falling below the lower temperature threshold are higher (8-12%) in Moulvibazar and Hobiganj compared to other wheat-growing areas. It is important to note that these probabilities are based on model projections and may vary based on local conditions and other factors (Figure 23).

When wheat was sown early with the historical climate data, the probability of exceeding the upper temperature threshold (30 °C) at the vegetative stage was 1.2-2.2% for most of Barisal and Chittagong divisions and two districts of Sylhet division. The probabilities of such threshold exceedance with the recent and long-term climate also followed similar geographical patterns, albeit slightly higher (2-6 and 4-6%, respectively) than for historical climate. For optimum sowing too, regardless of climatic period, the probability of upper temperature threshold exceedance was similar to early sowing (1-2.6%). The late sowing also showed a similar pattern (1.2-1.8, 3-4, and 4.0% respectively for the three climatic periods), albeit with higher probabilities for the southeastern and northeastern parts of the country (Figure 24).



Above: Wheat growing in Bangladesh. Photo Credit: Fahad Kaiser

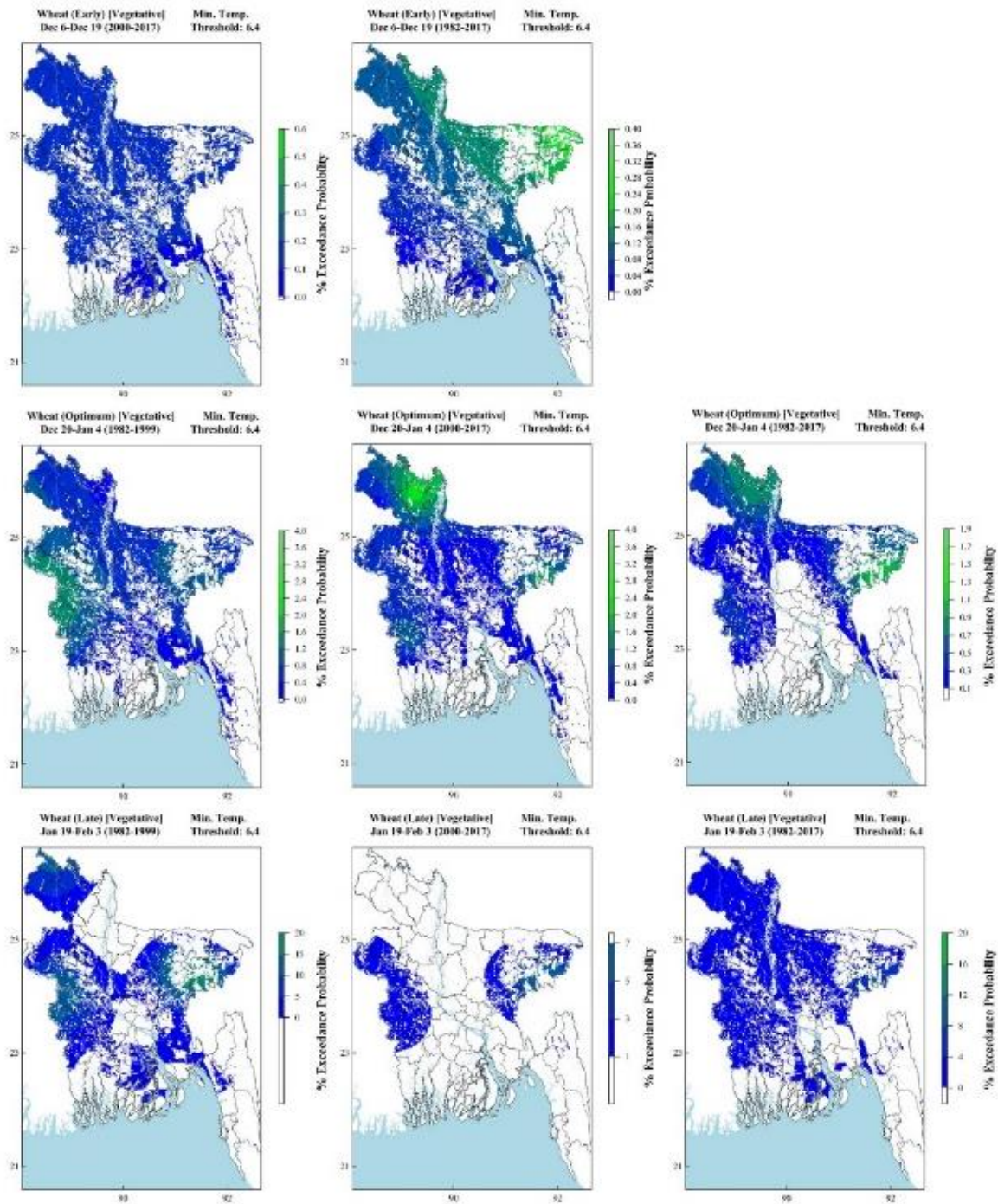


Figure 23. Exceedance probabilities for the lower temperature threshold (6.4 °C) during the vegetative stage of wheat were calculated for the periods of 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) for when wheat was sown early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

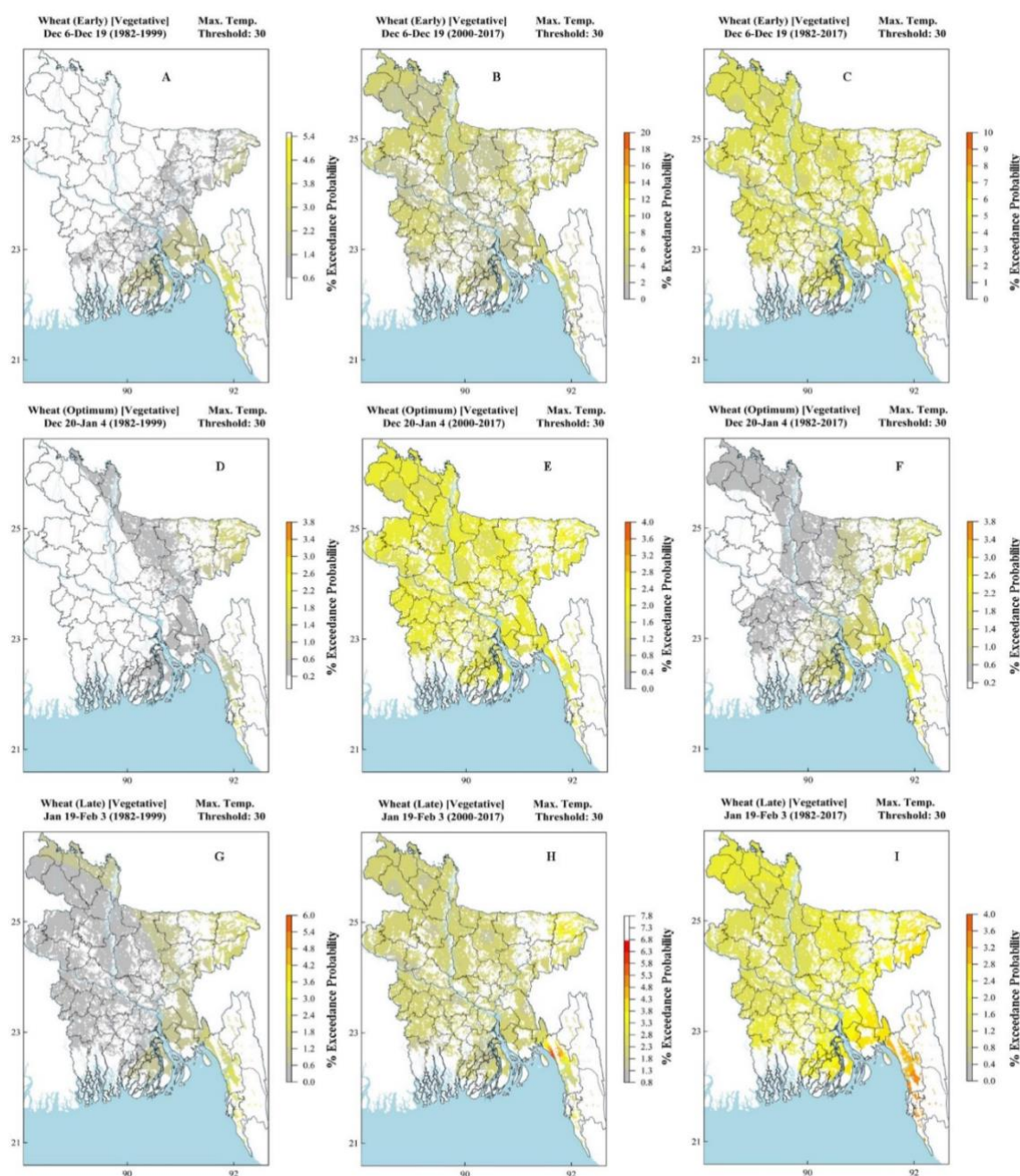


Figure 24. Exceedance probabilities for the upper temperature threshold (30 °C) during the vegetative stage of wheat from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late.

3.6.3 Heading and flowering

Based on our systematic literature review, it was found that the lower and upper temperature thresholds for the heading and flowering stage of wheat are 6.4°C and 32°C, respectively. Expert consultation revealed that the crop is likely to reach these stages between December 16-29, December 30 – January 14, and January 29 – February 13 for early, optimum, and late sowing, respectively. As these stages occur in spring with warmer temperatures, the likelihood of exceeding these

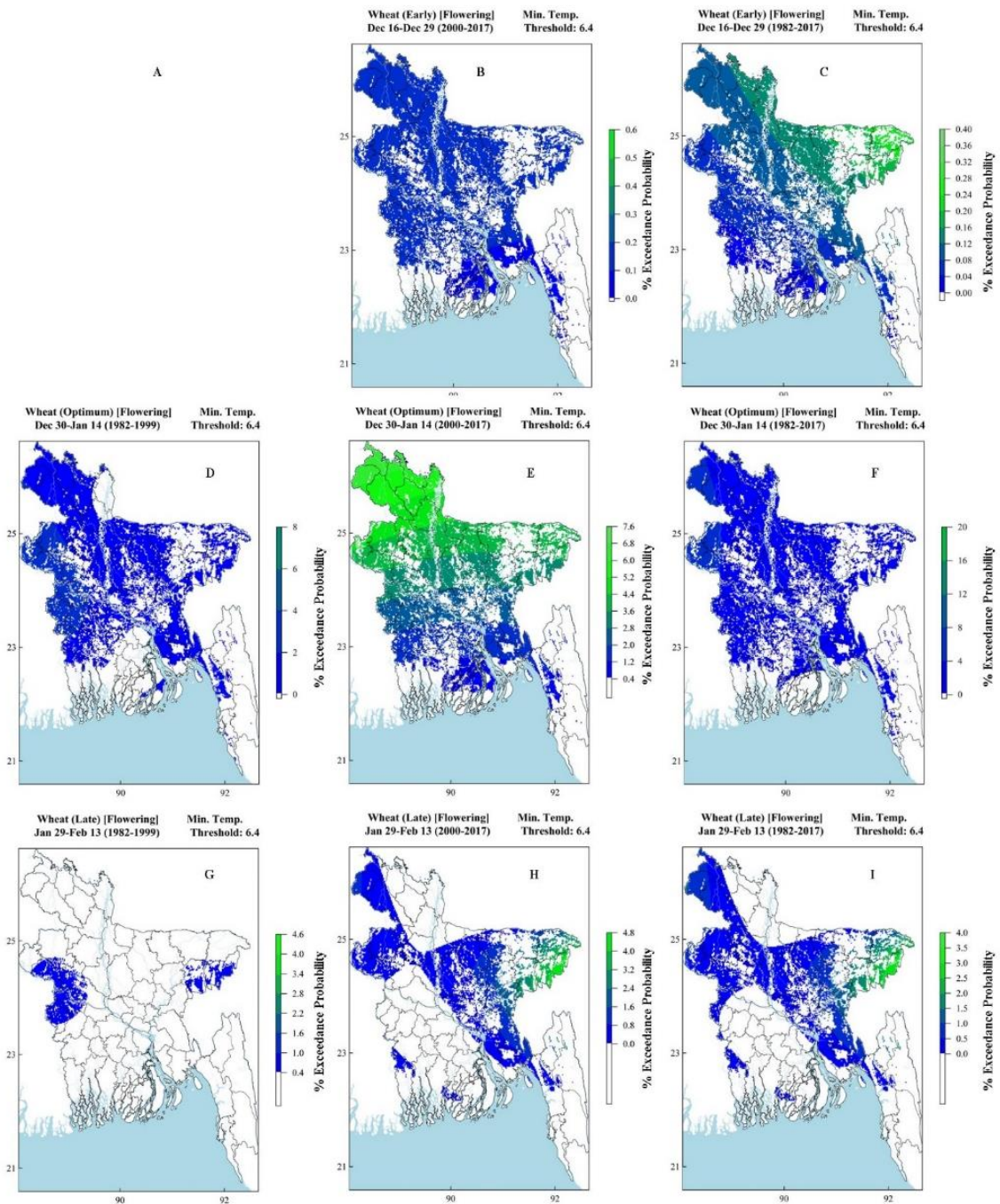


Figure 25. Exceedance probabilities for the lower temperature threshold (6.4°C) during the heading and flowering stage of wheat from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

thresholds is negligible (<1%) when the crop is sown early, regardless of the climate period. However, for optimum sowing, the probabilities of threshold exceedance are higher (4-6%, 5.2-6.8%, and 8-12% for the three climatic periods). While the

probabilities of threshold exceedance vary with historical and long-term climates, their distribution patterns remain similar. Recent climate data indicates a higher risk of temperature stress in the north-western and north-eastern parts of the country (Figure 25).

According to our analysis, when wheat was sown late with recent and long-term climatic data, the probabilities of low-temperature stress were 4.0-4.8% and 2.5-3.0%, respectively. These probabilities were more pronounced in the four districts of Sylhet division and Brahmanbaria and parts of the Comilla district of Chittagong



Above: A farmer in Bangladesh proudly displaying his crops. Photo Credit: Fahad Kaisar division.

For crops sown early or at an optimum time, our analysis suggests that the probability of exceeding the upper temperature threshold (32 °C) was negligible (<1%), which held true across all studied climatic periods. On the other hand, for late-sown wheat, the probability of heat stress was slightly higher (i.e., 1.1-3.1%) across the three climatic periods and was spread over north-eastern and south-eastern parts of the country (Figure 26).

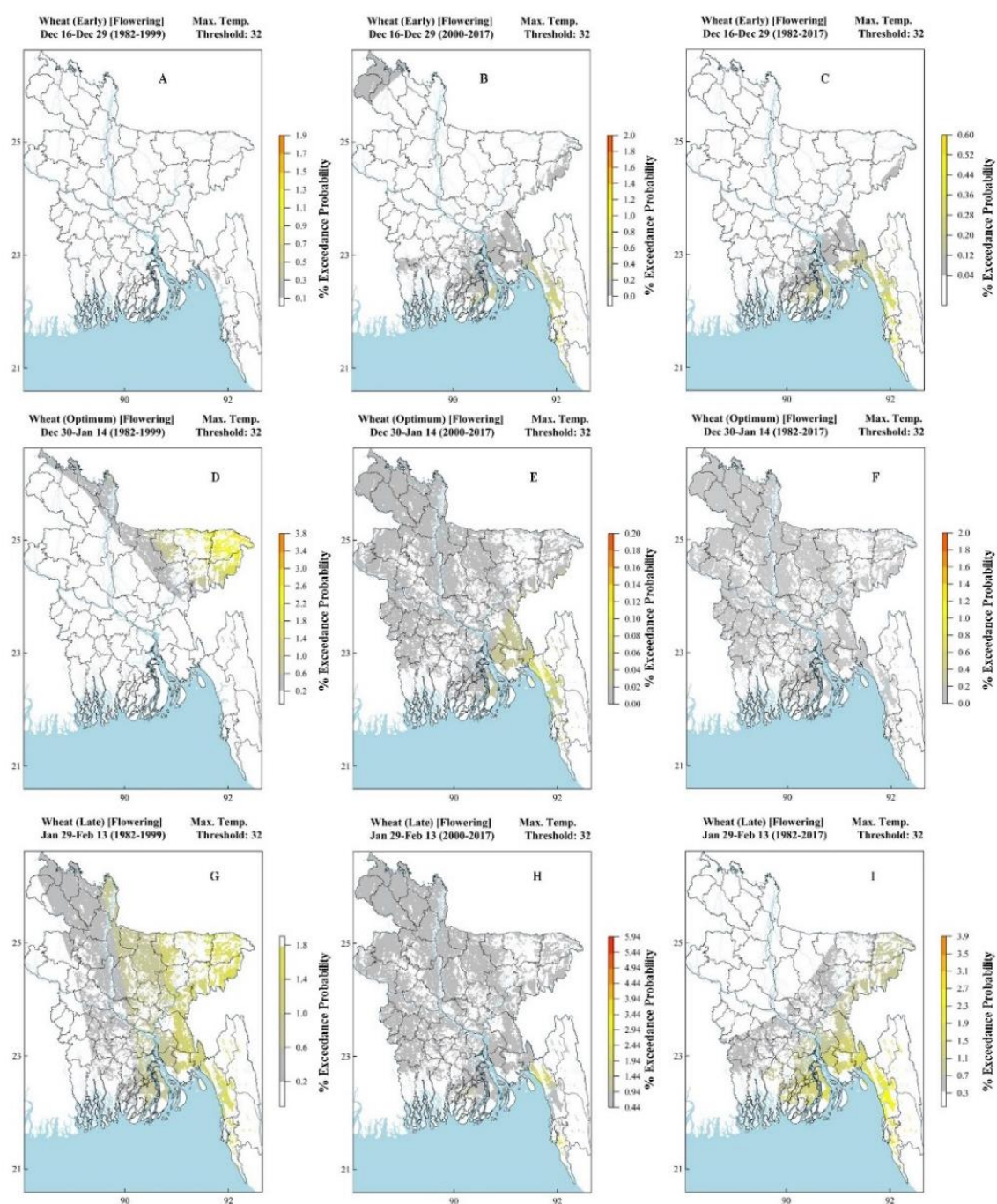


Figure 26. Exceedance probabilities for the upper temperature threshold (32°C) during the heading and flowering stage of wheat were analysed from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) when sown early, at optimal or recommended dates, and when sown late.

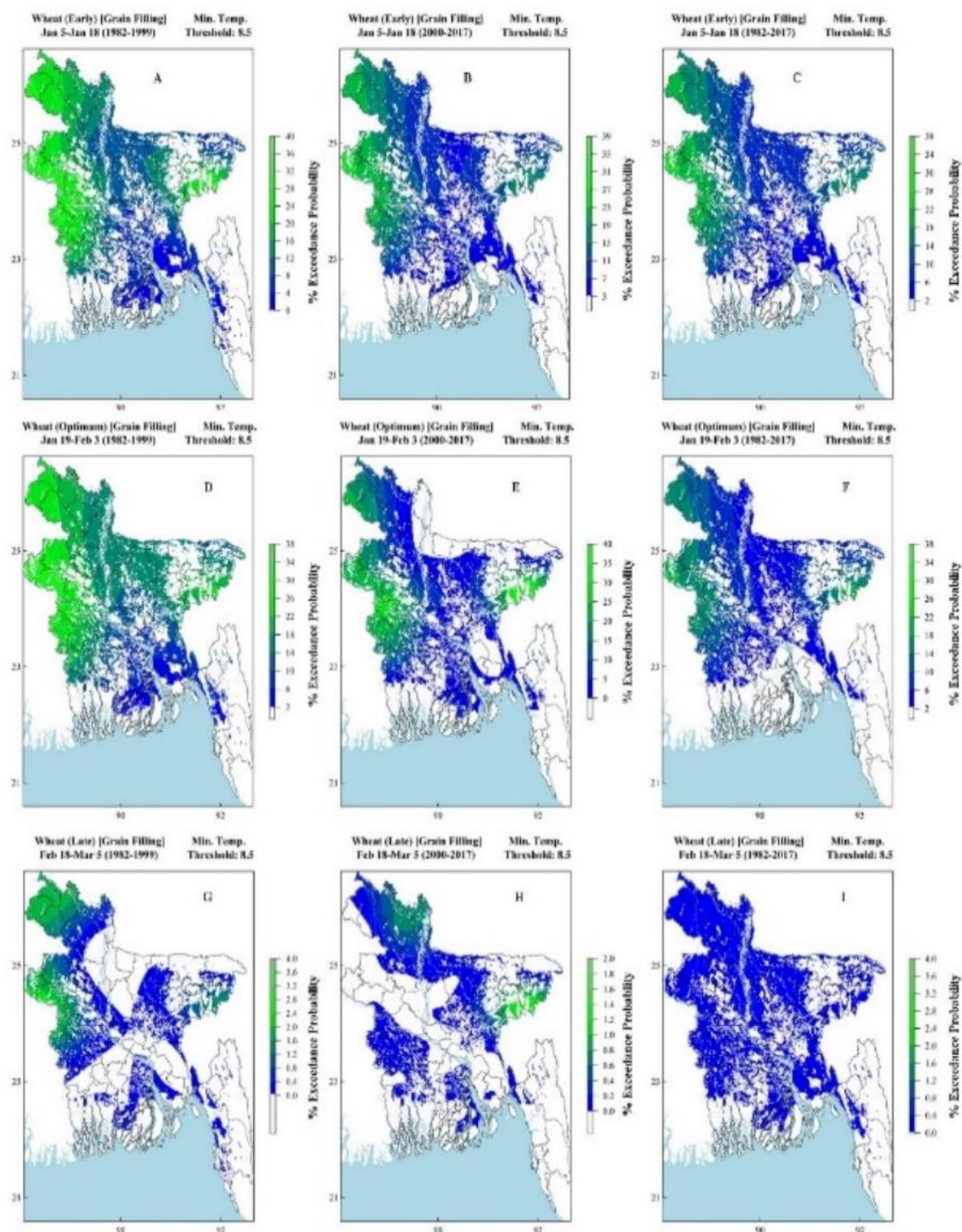


Figure 27. Exceedance probabilities for the lower temperature threshold (8.5°C) during the grain filling stage of wheat were calculated for the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) under different sowing times: early, at optimal or recommended dates, and when sown late.

3.6.4 Grain filling

Based on our consultations with researchers, the grain-filling stage for wheat sown under early, optimum, and late conditions will likely occur between January 5th-18th, January 19th-February 3rd, and February 18th-March 5th, respectively, across Bangladesh. During this stage, the probabilities of falling below the low temperature threshold were found to be 20-28%, 23-30%, and 22-20%, respectively, for each of the three climatic periods. The risk of cold stress appears to be concentrated in several districts in the northwest (Thakurgaon, Panchogarh, Dinajpur, Nagaon, Chapainababgonj, and Rajshahi), southwest (Kushtia, Meherpur, Chauadanga, Jashore, and Jheneidah), and northeast (Moulvibazar and Hobiganj) regions of the country. Similar spatial distributions were observed for the optimal timing of crop establishment, with slightly higher exceedance probabilities (22-35%) across the three climatic periods. However, for late-sown crops, the risk of cold stress was lower (0.8-2.8%), but still concentrated in the north-western and north-eastern parts of the country (Figure 27).

After conducting consultations with experts, it was found that the risk of exceeding the upper temperature threshold during the grain-filling stage is quite low across all climate periods, albeit with similar spatial distribution patterns as observed with the low temperature threshold. However, the risks were significantly higher in the northwest (Rajshahi, Chapainababganj), southwest (Kushtia, Meherpur, Chauadanga, Magura, Narail, Rajbari, Faridpur, Madaripur, Shariatpur, Khulna, Bagherhat, Pirojpur, Jashore, Barishal, Patuakhali, Bhola) and eastern districts (Chattogram, Moulvibazar, and Hobiganj), with exceedance probabilities of 12-20%, 20-32%, and 15-31%, respectively, for the three climatic periods (Figure 28).

3.7 Thermal thresholds exceedance for various critical development stages of maize

3.7.1 Sowing and germination

After conducting a systematic literature review and consulting with experts, analysed data suggested that sowing maize early in Bangladesh has no chance of low-temperature exceedance across the country, regardless of the climatic period. For optimum sowing and historical climate data, the probability of low-temperature exceedance is extremely low (<1%) (data not shown). However, if maize is sown late, the probability of low-temperature exceedance is between 8-20% for all climatic periods studied, particularly in most districts of Rajshahi, Rangpur, and Khulna divisions, but not in southern districts (as shown in Figure 29). Additionally, there is no chance of exceeding upper-temperature thresholds during the sowing and germination stages in any of the districts, regardless of planting times or climate periods. Therefore, no maps were generated for these thresholds.

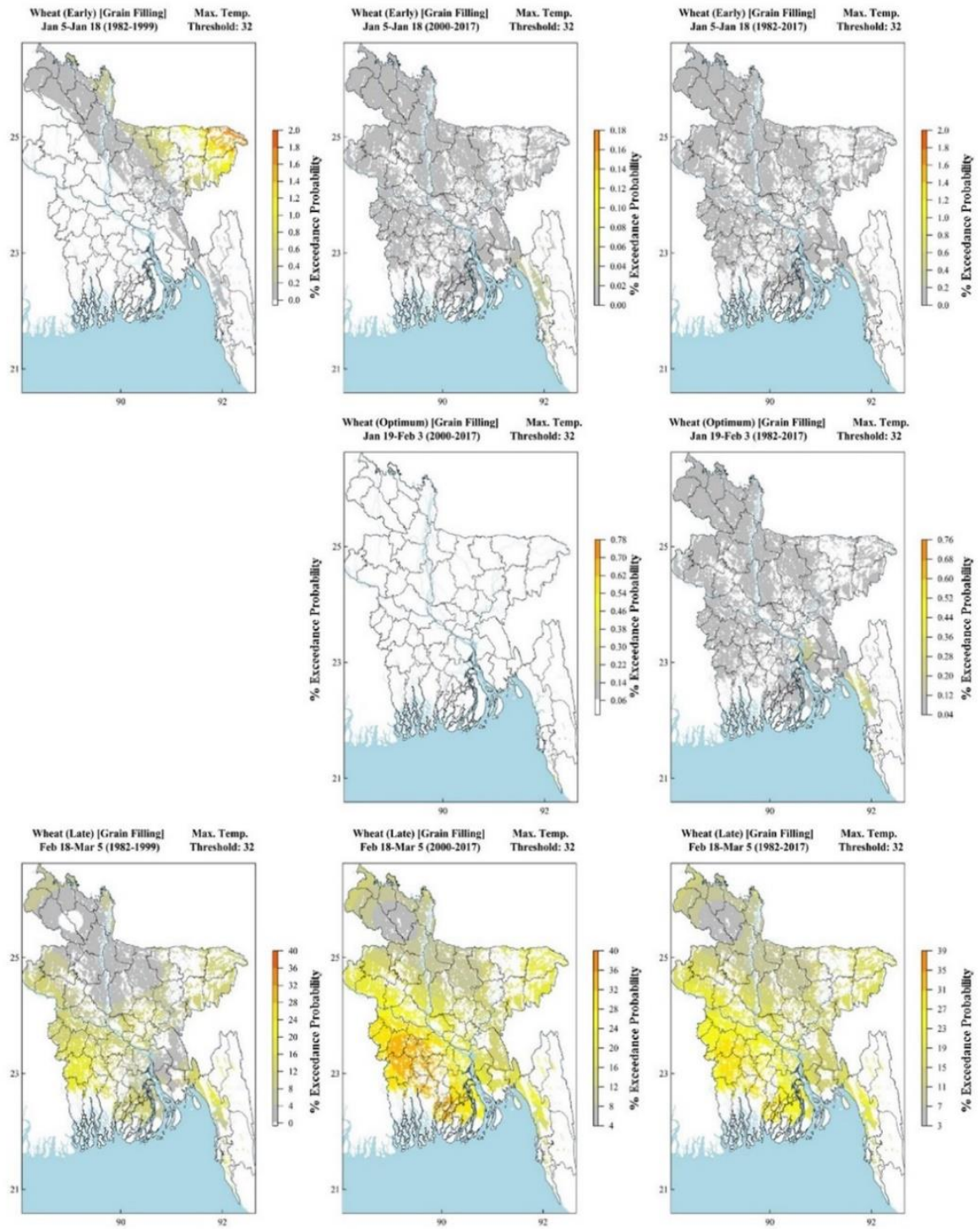


Figure 28. Exceedance probabilities were calculated for the upper temperature threshold (32°C) during the grain filling stage of wheat for the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), considering different sowing times: early, at optimal or recommended dates, and late. Note that maps were not generated for simulations that returned only zero probability values.

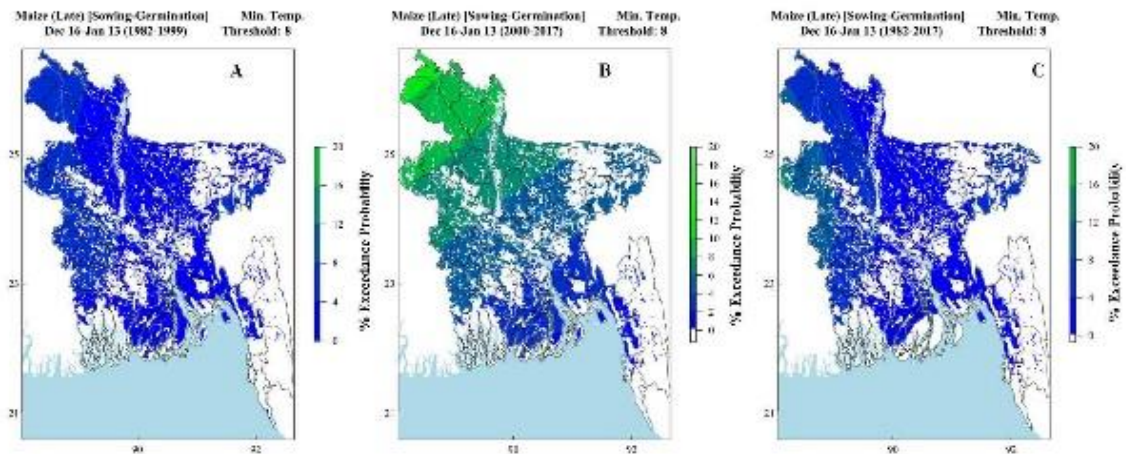


Figure 29. Exceedance probabilities for the low temperature threshold (8°C) at the sowing and germination stages of maize were calculated from data covering the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), under early, optimal or recommended, and late sowing conditions. Note that maps were not generated for simulations that returned only zero probability values.



Above: Farmer in Bangladesh transplanting rice by machine. Photo Credit: Abdul Momin

3.7.2 Vegetative stage

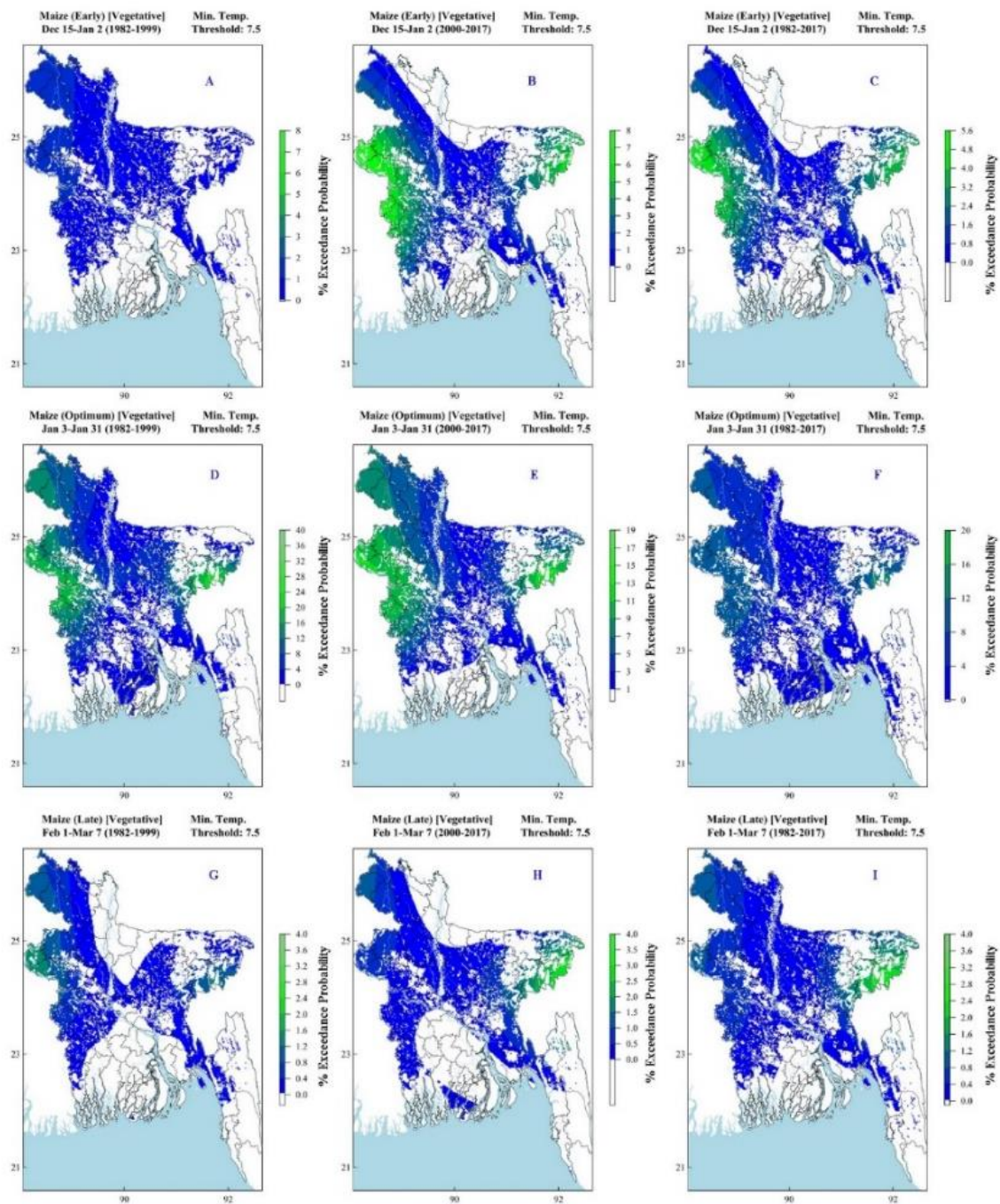


Figure 30. Exceedance probabilities for the lower temperature threshold (7.5°C) during the vegetative stage of maize were calculated for the periods 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) for different sowing times: early, at optimal or recommended dates, and late. Note that maps were not generated for simulations that returned only zero probability values.

Regardless of the climatic period studied our data suggest that when maize is sown early (October 15 - November 14), at optimum (November 15 - December 15), or late (December 16 - January 13) conditions, the crop is likely to reach the

vegetative stage during December 15 - January 2, January 3 - 31, and February 1 - March 7, respectively. Our examination of early sowing and historical climate data suggested there is minimal chance of the crop exceeding the low temperature threshold during the vegetative stage. However, when using more recent and long-term climates, there is a 5-8% probability of exceeding the threshold in two western districts of Rajshahi division, three southern districts of Khulna division, and two north-eastern districts of Sylhet division. Conversely, when maize is sown at the optimum time, the probabilities of exceeding the lower temperature threshold are higher (16-24%, 9-13%, and 8-12% for the three climatic periods, respectively) since the vegetative stage occurs during the colder period. The most affected districts for low temperature stress are the seven districts in Rajshahi, Rangpur, and Khulna divisions, and three northeast districts in Sylhet division. For late-sown maize crops, the vegetative stage also occurs late during the winter-to-spring transition period, and hence the probability of exceeding the low temperature threshold is low (<2 to 4%) for all north-western, western, southern, and north-eastern districts across all of the climatic periods studied (Figure 30).

Similarly, there is no chance of exceeding the upper temperature threshold during the vegetative stage for crops sown early or at the optimum time, as this stage occurs during the mild, colder period of the year. However, for late-sown crops across all studied climatic periods, there is a limited chance of exceedance (0.4 to <4.0%) in parts of Khulna and Rajshahi division as temperatures begin to warm up during this stage.

Silking and tasselling

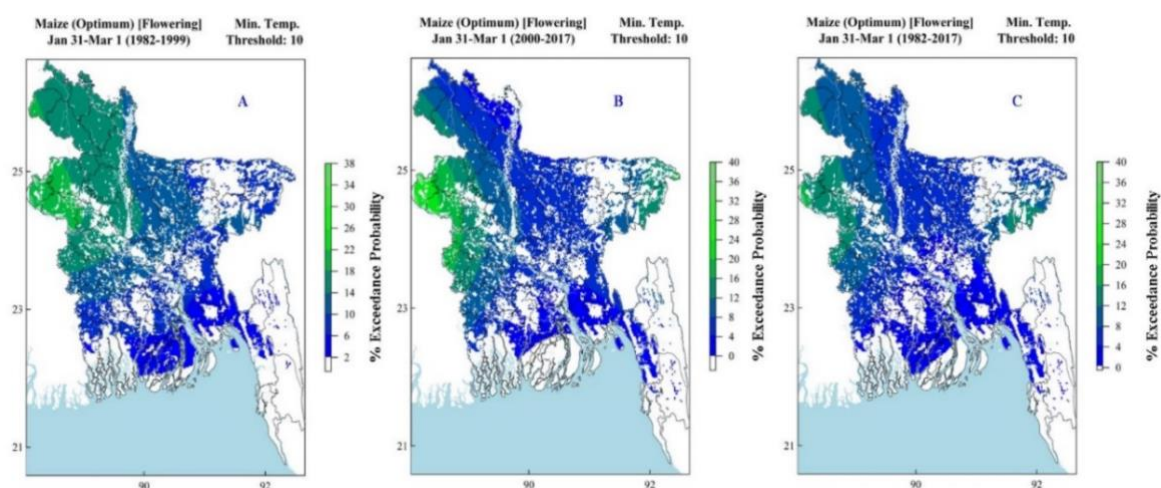


Figure 31. Exceedance probabilities for the low temperature threshold (10°C) during the silking and tasselling stage of maize were assessed for three periods: 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) for three different sowing times: early, at optimal or recommended dates, and when sown late. Note that maps were not generated for simulations that returned only zero probability values.

Our consultation with experts and analysis suggests that regardless of the climatic periods and locations, maize crops sown early, at the optimum time, or late are likely to reach the silking and tasselling stage during December 29 to January 30, January 31 to March 1, and March 2 to 22, respectively. For early-sown maize, we were unable to generate maps for the exceedance of the low -temperature threshold at the silking and tasselling stage for any climate period studied, as the CDFs returned zero probability values. However, for maize sown at the optimum time with historical climate, the probability of exceeding this threshold ranges from 22-38% in two districts in Rangpur division, three in Rajshahi division, two in southern division, and two in Sylhet division. A similar pattern was observed for optimum sowing under the recent and long-term climatic periods, with probabilities of exceedance ranging from 16-36% and 12-20%, respectively. Late-sown maize, with flowering occurring late in the season, has a minimal probability of exceedance of the low-temperature threshold (<2%) under different climatic periods (Figure 31).

Conversely, the mapping of exceedance probabilities for the upper temperature threshold for maize at silking and tasselling reveals clear patterns across locations and climatic periods, with the most significant changes in threshold exceedance being observed in the southern and southwestern parts of the country. Late-sown crops have a probability of exceeding this threshold ranging from 16-32%, 20-27%, and 18-30% for the historical, recent, and long-term climatic periods, respectively. All districts of Khulna and Rajshahi divisions, as well as some districts of Dhaka division, appear to be susceptible to high-temperature stress (Figure 32).

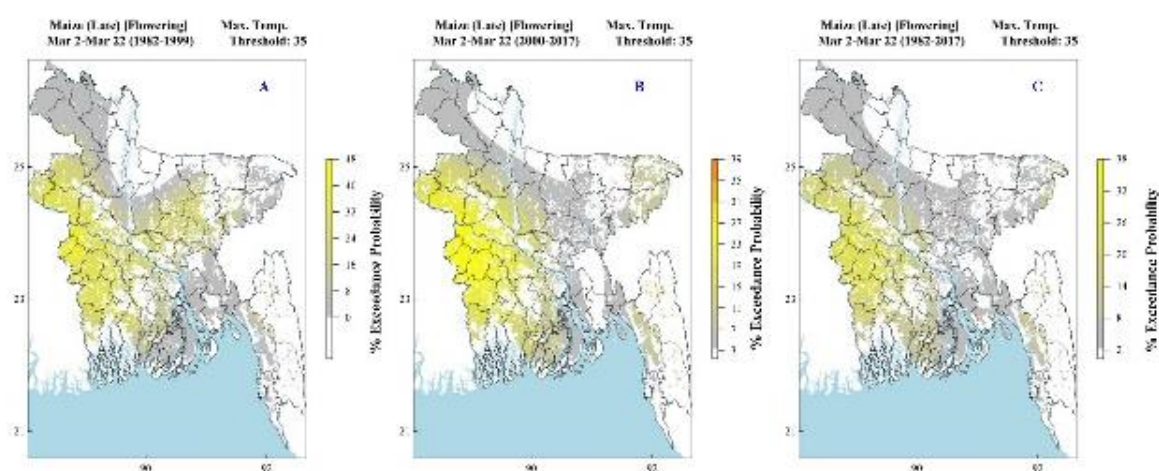


Figure 32. Exceedance probabilities for the high temperature threshold (35°C) during the silking and tasselling stages of maize were calculated for the climatic periods of 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term) under different sowing conditions: sown early, sown at the optimal time, and sown late. Note that maps were not generated for simulations that returned only zero probability values.

3.7.3 Grain-filling stage

When maize is sown at early, optimum or late conditions, our expert consultations suggested that the crop is likely to achieve the grain filling stage during February 2 – March 2, March 3 – 31, and April 1 – 29, respectively, regardless of the climatic

period or location. For crops sown early, there is a high probability of low-temperature threshold exceedance during the grain-filling stage, ranging from 36-52%, 34-58%, and 48-78% for historical, recent, and long-term climatic periods, respectively, throughout the country. Exceedance probabilities are especially high in two districts each in Rangpur, Rajshahi, Khulna, and Sylhet divisions. Sowing at the optimum time reduces the probabilities of exceedance to 22-31%, with minor differences between the three climatic periods. However, higher probabilities may occur in Nilphamari, Lalmonirhat, Rangpur and Kurigram districts of the Rangpur division and Moulvibazar and Hobiganj districts of the Sylhet division. On the other hand, for late-sown maize, regardless of climate period or location, there is little to no chance of exceeding the low-temperature threshold (Figure 33).

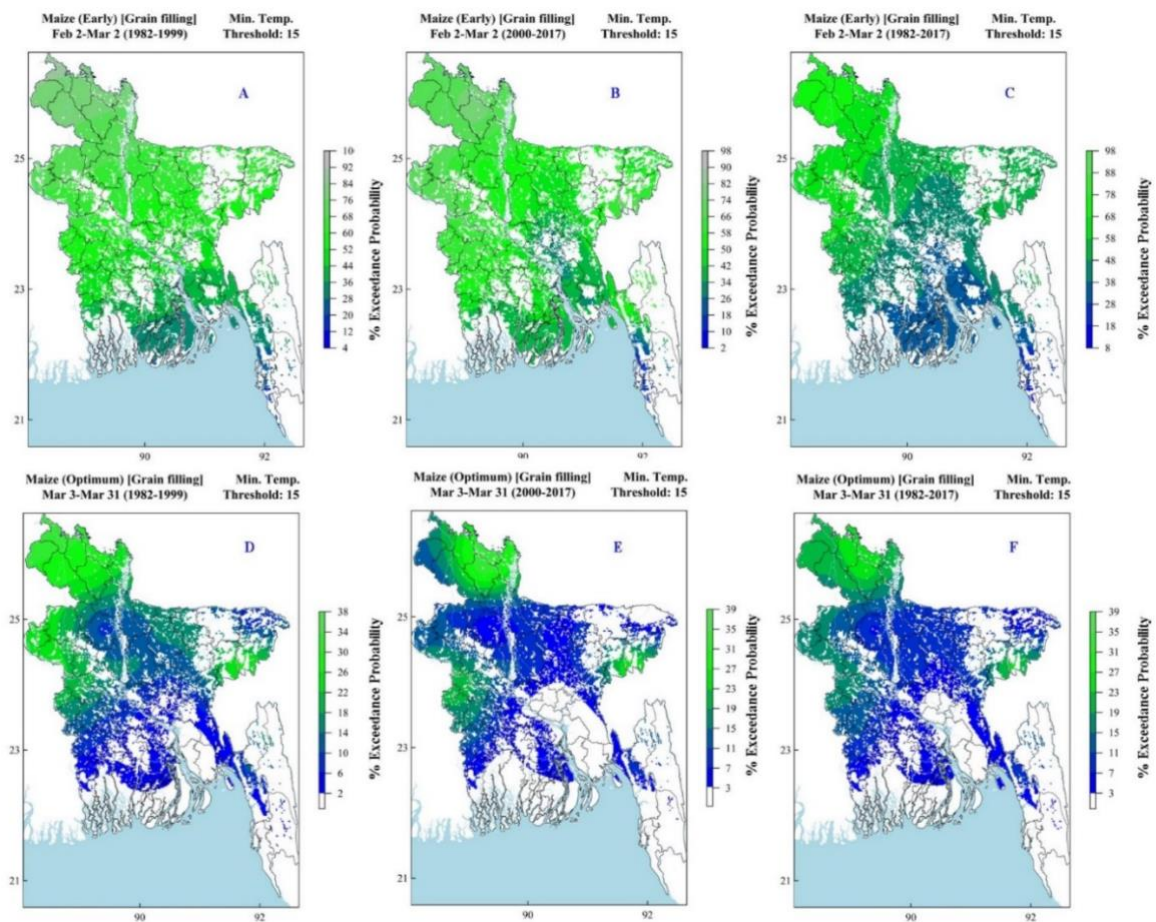


Figure 33. The exceedance probabilities for the low temperature threshold (15°C) during the grain filling stage of maize were calculated for the climatic periods from 1982-1999 (historical), 2000-2017 (recent), and 1982-2017 (long-term), considering early, optimum, and late sowing times. It should be noted that no maps were generated for simulations that resulted in zero probability values.

We next discuss high temperature stress for maize. Our analysis indicates that when maize is sown early, regardless of the climate periods studied (1982-1999, 2000-2017, or 1982-2017), the likelihood of surpassing the upper-temperature threshold is relatively low, ranging from 4 to 6%. This is especially true for the Khulna division and some districts of the Rajshahi division. However, if the crop is established slightly later, the probability of exceeding the threshold increases as it

reaches the grain-filling stage during the hot period. The probability of exceedance ranges from 38 to 54% for recent climate and 30-60% for long-term climate, following similar patterns for the districts affected (Figure 34).

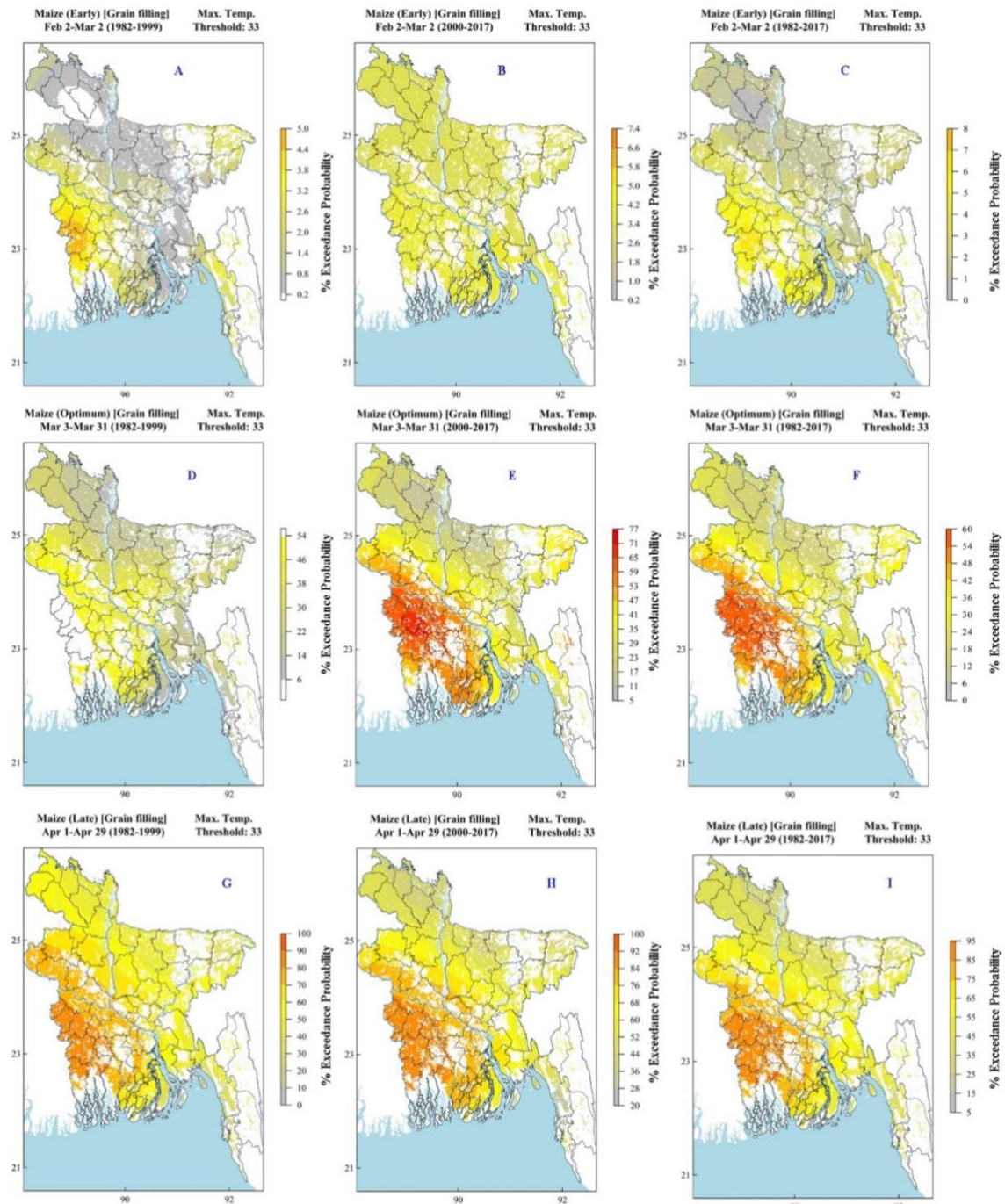


Figure 34. The probabilities of exceeding the high temperature threshold (33°C) during the grain-filling stage of maize were calculated for three different periods: historical (1982-1999), recent (2000-2017), and long-term (1982-2017). The exceedance probabilities were determined for three sowing times: early, optimal, and late.

4. Practical application of this study's findings

This study aimed to assess the sensitivity and tolerance of maize, wheat, and rice to high and low temperatures and generate maps of the exceedance of high and low temperature thresholds for Bangladesh. Previous studies have established that each crop species has a generally applicable cardinal temperature range that is optimal for its growth, development, and yield. The tolerance of these species to temperatures beyond this range varies. When high or low temperature thresholds are exceeded during particular phenological stages of each crop, yield reductions may be expected (Farooq et al., 2011; Hatfield et al., 2011). Additionally, it is important to note that there may be variation in these thresholds among different crops and even within different varieties of the same species. This is particularly the case for varieties bred to be tolerant of high or low thermal stress. For the purposes of this report, we only examined the three major cereals, with a particular emphasis on tropical indica rice given its prominence in Bangladesh.

The methodology described in subsection 2.4 (Generation of the probability of exceedance thermal stress maps) was used to generate country-level maps for upper and lower temperature thresholds for each of the three major cereals in Bangladesh, including tropical indica rice. Out of 414 attempts, 260 maps were successfully produced while 154 did not generate graphical outputs because the exceedance probability values being zero. Among the maps generated by our algorithms, 207 and 108 were for upper and lower temperature thresholds, respectively.

However, it should be noted that generating and utilizing such maps has limitations due to the variability in the percent probabilities of exceedance, which can vary across different species, their varieties, studied time periods, and locations in the country. Our systematic literature review approach should therefore be taken with some degree of caution as we did not segment the dataset. Rather, we took a broad approach to the consideration of crop species, as our goal was to assess broad trends in temperature stress levels at a national level. Moreover, when considering the country of Bangladesh as a spatial unit, farmers would in reality also be planting and harvesting multiple varieties of the same species – including both thermal stress tolerant but most likely intolerant varieties that remain common in Bangladesh (Islam et al., 2013; Maniruzzaman et al., 2018). It is also worth noting that while weather data shows a trend of increasing average night and day temperatures across the country for the time scale 2000-2017 compared to 1982-1999, changes do not appear to be very large. It is also important to consider that there may be differences in these thresholds between crops and varieties within a crop, which is a subject for future and more detailed research. Our study utilized data only to 2017 as these were the years when the Bangladesh Meteorological Department was able to provide complete datasets requisite for our analysis. The year 2023, however, has been one of the hottest in global history (Koons, 2023; NASA, 2023); as such, our analysis should be considered preliminary and indicative, with additional research needed with a fully up-to-date weather dataset to confirm or reject particular results.

4.1 Temperature sensitivity and exceedance of threshold temperatures in rice

4.1.1 Boro rice

Most studies examining the impact of temperature stress on rice productivity in Bangladesh focus on winter season *boro* rice, which is generally sown from the end of October to the end of December (Table 1). Our data suggest that *Boro* rice is susceptible to temperatures below 10 °C during December and January, when it is in seedbeds or shortly after transplanting. If cold temperatures persist for more than seven days, the crop can fail completely (Ahmed et al., 2016). *Boro* rice is also vulnerable to low temperatures during the reproductive stage, especially at the panicle initiation and flowering stages (Kabir et al., 2015).

Our analysis, which is backed by the literature, suggests that *boro* rice is vulnerable to low-temperature stress during sowing and germination regardless of the climatic period and location. The western and north-western regions of Bangladesh tend to be cooler than other parts of the country. Cold stress is more likely to affect the *boro* rice seedlings, regardless of the climatic period and sowing time. At the maximum tillering stage, the probability of encountering cold stress appears to be moderately high, especially for early and optimally sown crops. High temperatures towards the end of the growing season can also be detrimental, resulting in faster development, shortened reproductive phases, and reduced yields (Ishimaru et al., 2010; Islam, 2011; Jagadish et al., 2007; Krishnan et al., 2011; Rezaei et al., 2015; Yoshida, 1981). The heading and flowering stages are particularly susceptible to both low and high temperatures (Kabir et al., 2015; Jagadish et al., 2007; Yoshida, 1981). At the ripening stage, high-temperature stress is more likely to occur. High temperature generally prevails in March through May in Bangladesh (Maniruzzaman et al, 2018).

4.1.2 Aus rice

There is limited information available on the low or high temperature thresholds specifically for spring *aus* and summer *aman* rice in Bangladesh. Therefore, we evaluated the impact of exceedance of threshold temperatures for based on general literature uncovered by our systematic review for indica rice. Our research using historical climate data suggests that *aus* rice in Bangladesh does not experience cold temperature-related stresses throughout its life cycle. However, during the growing season, the probability of encountering stress from the exceedance of high temperature thresholds likely to be high at all phenological stages, with probabilities varying temporally and spatially across the country. Krishnan et al. (2011) reported that *aus* rice in Bangladesh could be exposed to high temperatures above 35°C from the end of March to early May, coinciding with anthesis, which can lead to high sterility and reduced yield. Night temperatures during the *aus* rice growing season are always above low temperature thresholds at different crop phenological stages.

4.1.3 Aman rice

Aman rice is predominantly cultivated in Bangladesh under rainfed conditions during the summer monsoon season, with sowing timed to coincide with the onset of the monsoon season. As farmers await sufficient rainfall to prepare the

paddy fields, frequent precipitation during the growing season and maintenance of a flood water layer helps moderate both soil and air temperatures. Our data suggest that maximum temperatures range between 29 and 35 °C for *aman* rice in Bangladesh, which are approximately at or slightly above the optimum temperatures identified in our systematic literature review.

However, according to our data, there is little to no probability of encountering low-temperature stress during the sowing and germination, seedling, and maximum tillering stages of *aman* rice, at least when considering historical data. However, low temperatures could impact the heading, flowering, and ripening stages of late-sown *aman* rice, especially in the cooler northern and northwestern regions of the country (Rajshahi, Rangpur, and Sylhet divisions). In these areas, night temperatures can drop below the low-temperature threshold values (17 °C and 12 °C during heading and flowering, and ripening stages, respectively), typically in November.

Similarly, the probability of exceeding the upper-temperature threshold during the sowing of *aman* rice is not likely, but there is some likelihood (10-20%) of such exceedance during the seedling and maximum tillering stages, particularly with more recent and long-term climatic data. There is also little probability (4-7%) of exceeding the upper-temperature threshold during the heading and flowering stages. However, early sown *aman* rice may encounter high-temperature-related stresses during the ripening stage throughout Bangladesh, except in the Chittagong hill tracts region in the southeast.

4.2 Temperature sensitivity and exceedance of threshold temperatures in wheat

Our threshold maps and use of historical climate data indicate that there is no likelihood of low temperature threshold exceedance during the sowing and germination stage of wheat, but there is a slight possibility of exceeding the high temperature threshold. During the flowering stage, there may be slight stress due to both low and high temperatures, while during the grain filling stage, there is a significant likelihood of low temperature threshold exceedance, particularly when wheat is sown early or at the optimum time. This is especially true for most districts in the Rajshahi, Rangpur, and Khulna divisions. In contrast, high temperature susceptibility is likely in the Khulna and Barishal districts when wheat is sown late.

Like most species, wheat has a specific range of cardinal temperature sensitivity for each stage (Farooq et al., 2011). In Bangladesh, the primary temperature-related challenge relates to above-optimal temperatures towards the end of the growing season, from February to April. Studies have demonstrated that when the diurnal minimum and maximum temperatures were 12 °C and 22°C, respectively, the physiological impact of heat stress on wheat occurred during the reproductive and grain-filling stages (Farooq et al., 2011; Lobell et al., 2008, 2012; Reynolds et al., 1994; Rezaei et al., 2015). Stress is expressed as floret abortion during anthesis, as temperatures above 30°C during floret formation caused complete sterility, pollen sterility, tissue dehydration, lower net CO₂ assimilation, and increased respiration during the reproductive phase (Farooq et al., 2011; Tashiro and Wardlaw, 1989).

4.3 Temperature sensitivity and exceedance of threshold temperatures in maize

The threshold maps indicate that for summer *rabi* season maize, low temperature stresses are negligible throughout the country, except for some districts in the western, north-western, and north-eastern regions. However, if maize is sown late, the probability of low temperature threshold exceedance during the growth stages is likely (8-20%). During the vegetative stage and based on our data, the probability of lower temperature exceedance is almost zero to 24%. Early sowing can avoid both lower and upper-temperature stresses during flowering. On the other hand, optimum time and late-sown crops appear to be affected by both low and high-temperature stresses at flowering. At the grain filling stage, higher susceptibility to both low and high-temperature stresses is more widespread, covering the western, north-western, and north-eastern districts of the country.

Maize is a C4 crop and relatively tolerant to high temperatures, with an optimal photosynthesis range of temperatures from 33 to 38 °C (Yadav et al., 2016). However, high temperatures during grain filling can reduce yield since processes such as grain set and the length of time grains are formed are temperature-sensitive (Dupuis and Dumas, 1990; Jones et al., 1984; Schoper et al., 1987; Yadav et al., 2016). Additionally, maize, like rice, poorly tolerates long periods of temperatures below 10 °C, which can delay the process of grain filling. Higher temperatures, on the other hand, can accelerate physiological process, and reduce the period of time for optimal solar inception, resulting in yield reduction (Yadav et al., 2015).

4.3.1 Management strategies in cereals to alleviate temperature stresses

To mitigate the negative impacts of temperature stresses on crops, it's essential to implement climate-smart and well-planned adaptation strategies. Since different species exhibit varying tolerances during different growth stages, it is also important to provide farmers with tailored management recommendations to safeguard their crops.

When *boro* rice is in the seedling stage, there is a risk of cold injury if a severe cold spell occurs. If the crop is in the booting stage during cold weather, it can result in reduced grain formation. Furthermore, the panicle may not emerge fully, causing the rice grains in the upper part of the panicle to die, and the number of spikelets per panicle may change abnormally. Additionally, during a cold wave, seedlings are susceptible to cold-related damage, potentially leading to their death (BRRI, 2022). For *boro* rice, our dataset suggests optimal conditions for grain filling include a night temperature of 12-13 °C and a daytime temperature of 23-24 °C, particularly from the late booting to the dough stage. However, even if the night temperature rises within five to six days (during seedling establishment), there is only a slight risk of increased sterility. On the other hand, when the night temperature falls within the ideal range, but the daytime temperature exceeds 28-29 °C, the risk of sterility is reduced.

In the context of rice cultivation, particularly during cold weather, it is advisable to consider specific strategies for protecting rice seedlings to optimize crop yield and

mitigate potential adverse effects of low temperatures. Based on recommendations from the Bangladesh Rice research Institute (BRRI), the following measures can be recommended as effective practices:

1. **Water Management:** Maintaining an appropriate water level in the seedbeds and the main field is important. During cold spells when seedlings are dry in the morning and moist in the evening, it is recommended to keep 3-5 cm of water in the field. This practice helps protect the seedlings from cold damage and promotes healthy growth. It is particularly suitable for regions with a central climate.
2. **Polythene Covering:** In regions prone to fluctuating temperatures, such as northern and northwestern areas and places like Shrimangal, continuous or night-time polythene covering in hoop houses may be necessary to shield the seedlings from temperature variation. However, when using polythene covering, it is advisable to remove the polythene 4-5 days before transplanting to prevent any negative impact on the seedlings.
3. **Transplanting Age:** When transplanting seedlings during winter, it is recommended to use seedlings that are at least 35-45 days old. This practice reduces seedling mortality during colder periods, maintains seedling vigor, and contributes to higher crop yields. Normally, rice tends to yield best with younger seedlings (Pasuquin et al. 2008), although under the unique winter cultivation conditions associated with *boro* rice and the risk of cold injury, slightly older seedlings tend to be recommended.
4. **Flowering and Grain-Filling Stages:** During the flowering and grain-filling stages, if there is a prolonged cold period, maintaining a water level of 15-20 cm in the field can be beneficial to mediate diurnal microclimate fluctuation in the field.

Heat stress is also detrimental to rice crops, particularly late-sown *boro* rice, with temperatures exceeding 35 °C for 1-2 hours between 10 am and 12 pm during the flowering stage leading to excessive sterility. Delayed transplanting of *boro* rice, especially in May during the flowering stage in extremely hot weather, can also increase the risk of excessive sterility. High temperatures, especially during sowing and germination, can damage rice seeds, disrupt germination, and post-transplanting, during recovery from transplanting shock, cause seedling mortality (Ahmed et al. 2016).

In such circumstances, farmers have the option to delay sowing for a few days or provide irrigation to the seedbed to ensure adequate moisture for seed germination and seedling emergence. If temperatures exceed 35 °C during transplanting, farmers can consider postponing transplanting until temperatures are within the optimal range. Furthermore, post-transplanting, maintaining a standing water level of 5-7 cm in the rice field can effectively mitigate the adverse effects of heatwaves. These adaptive measures can help safeguard rice from the detrimental impacts of extreme heat stress (BRRI, 2022). This however may come with economic trade-offs, particularly for *boro* rice that requires water for irrigation as it is grown during the dry season (Mainuddin, et al. 2021).

During the booting stage, temperatures above 35 °C can cause spikelet sterility and reduce crop yield (Aghamolki, 2014). To minimize the damage, farmers can increase the depth of irrigation water or consider transplanting early and growing short-duration varieties. These management practices can also be applied to *aman* and *aus* rice to mitigate the effects of high temperature stress.

Very cold temperatures can also harm wheat seeds, causing delays in germination and decreased emergence of seedlings (Jame and Cutforth, 2004). Farmers can choose to delay wheat sowing for a few days to avoid the coldest spells and ensure more favorable conditions. Conversely, when experiencing high temperatures that exceed 33 °C, reduced seedling emergence may occur. To counteract this, farmers can employ strategies such as field irrigation to maintain adequate soil moisture and regulate soil temperature fluctuation, potentially mitigating the adverse impacts of high temperatures on seed germination and seedling establishment. These and other climate adaptive practices can contribute to better wheat crop resilience in the face of temperature-related challenges (Bell et al., 2015; Lobell et al., 2008)

When cultivating maize, it is prudent to refrain from planting during the *rabi* season in areas where temperatures regularly fall below 10 °C. To address temperature-related challenges in regions with a higher likelihood of temperature extremes, it may be advisable to explore alternative species better suited to prevailing temperature conditions. Another effective strategy involves adjusting the timing of sowing to minimize temperature stress during critical growth phases. However, the feasibility of this approach depends on various factors, including cropping systems, land availability, and water management practices.

Furthermore, the adoption of stress-tolerant crop varieties exhibiting enhanced yield potential and resilience to multiple stressors such as cold, heat, drought, flood, and salinity are also paramount for ensuring stable crop yields. Simultaneously, harnessing the benefits of technological advancements also requires a well-developed system for the sales and distribution of quality seeds and propagation materials, as well as improved access for farmers to other inputs. In Bangladesh, crop varieties resilient to different stresses have been released for dissemination among farmers as part of government-backed adaptation strategies aimed at reducing climate vulnerability. Some of the varieties of rice, wheat and maize released by BRRI and BWMRI are listed below with their salient features.

BRRI has developed 49 *boro*, 47 *aman*, and 26 *aus* rice varieties. Out of the 49 *boro* varieties, only two are cold-tolerant: BRRI dhan36 and BRRI dhan55. The former is a short-duration rice variety that is cold, drought, and salt-tolerant, while the latter can also be cultivated as *aus* rice. BRRI dhan28, 36, 45, and BRRI dhan55 are short-duration *boro* varieties, with BRRI dhan55 also exhibiting drought resistance. Among the short-duration *T. Aman* varieties, BRRI dhan33, 39, 56, and BRRI dhan57 are notable, with BRRI dhan56 and BRRI dhan57 being drought-resistant. In the *aus* rice category, BRRI dhan42 and BRRI dhan43 stand out as drought-resistant varieties. BRRI has also developed seven hybrid rice varieties: BRRI Hybrid dhan1, 2, 3, 4, 5, 6, and BRRI Hybrid dhan7. Among these, BRRI Hybrid dhan2, 3, and BRRI Hybrid dhan4 are early-maturing (BRRI, 2022)

The wheat varieties developed by the Bangladesh Agricultural Research Institute (BARI) include BARI Wheat 25, 26, 27, 28, 29, 30, 31, 32, and 33 up to 2018. Subsequently, starting from 2019, the Bangladesh Wheat and Maize Research Institute (BWMRI) released BWMRI Wheat 1, 2, 3, and BWMRI 4. All varieties released by BARI and BWMRI exhibit some degree of heat tolerance, except for BARI Wheat 33 and BWMRI 1 and 2. In most cases, these heat-tolerant varieties can be planted later in the season, yet still yield well. Promising maize varieties released by BARI and now stewarded by BWMRI include Hybrid Maize 14, 15, and BARI Hybrid Maize 17. These varieties exhibit high heat tolerance, while BARI Hybrid Maize 12 and BARI Hybrid Maize 13 are tolerant to moderate drought conditions (BARI, 2019, BWMRI, 2023).

In general, irrigation can help mitigate high-temperature-related stresses by providing a cooling microclimatic effect at the field level. However, this may not always be feasible due to water availability constraints. Therefore, cultivating heat or temperature stress-tolerant crop varieties is generally practical and cost-effective. To avoid terminal heat stress in *rabi* wheat or maize, it is recommended to grow short-duration aman rice in sequence with rabi wheat or maize for earlier sowing (Ali et al., 2008). Short-duration *T. aman* rice varieties including BRRI dhan33, BRRI dhan39, BRRI dhan56, BRRI dhan57, BRRI hybrid dhan4, and Binadhan-7, can be harvested early, reducing turnaround time between and allowing *rabi* wheat or maize to be sown within the recommended dates. Alternatively, using single-pass machineries such as zero- or strip-till drills attached to power tiller-operated seeders can help establish wheat or maize rapidly within the recommended sowing dates and avoid terminal heat stress (Johansen et al., 2007).

5. Conclusions

In conclusion, the stability of food production faces considerable challenges due to climate change, population growth, and shifting dietary preferences, particularly in climate-vulnerable regions such as South Asia. The impact of climate variability and extreme weather events on major cereal crops can significantly affect the livelihoods of farmers. However, research in this area has been hindered by data limitations. This study addressed this gap by estimating the probabilities of thermal stress thresholds being surpassed for rice, maize, and wheat in different regions of Bangladesh during various growth stages. Our results provide detailed mapping the high likelihood of temperature-related stress during specific phenological stages for each crop, with variations across geographical regions and time periods. These findings offer valuable insights for research, agricultural decision-making, and crop planning in Bangladesh, emphasizing the importance of climate resilience strategies for food security in the face of climate change.

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Annex I. Papers used in systematic literature review to determine temperature stress thresholds for rice, wheat, and maize.

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