Climate Variability and Its Influence on Maize (*Zea mays* L.) Production Decline in Eastern Bhutan

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ABSTRACT

Maize is a staple food crop in eastern Bhutan, but its production has significantly declined in recent years, potentially due to the effects of climate change. Despite this, there has been limited research on the impact of climate variability on maize yield in the region. This study aims to assess climate variability trends and their effects on maize yields from 2006 to 2023. Using the Mann–Kendall trend test and Sen's slope estimation, the temperature and rainfall trends were analysed, while Pearson correlation and multiple linear regression were applied to examine the relationship between climate variables and maize yields. Minimum and maximum temperatures showed an upward trend increasing by 0.03°C and 0.06°C, respectively. In contrast, rainfall exhibited no clear trend but displayed significant year-to-year variability. While rainfall and minimum temperature had a weak influence on maize production and yield, maximum temperature had a significant positive impact, explaining 29% of the variation in production and 37% of the variation in yield. The remaining unexplained (71% for production and 63% for yield) suggest the importance of non-climatic factors and localized microclimatic conditions. This research emphasis the focus on non-climatic and microclimatic factors to fully understand the causes behind the declining maize production in the region. To enhance climate monitoring and develop more effective adaptation strategies for agricultural crops, it is recommended to establish additional weather stations beyond those currently operated by the National Centre for Hydrology and Meteorology (NCHM).

Keywords *Maize; Production; Rainfall; Temperature; Yield*

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1 Introduction

The agricultural sector employs 41.7% of the Bhutan's population and contributes 14.96 % to the GDP with 6.57 % from crops alone (National Statistic Bureau [NSB], 2024a; NSB, 2024b). Maize, the second most important cereal, is cultivated by 64% of rural households (Katwal & Bazile, 2020), and constitutes 62% of annual production in the eastern districts (National Statistic Bureau, 2023), serving as the staple food for this region. It plays a crucial role in food and nutritional security, accounting for 44% of the national food composition (Wangmo, 2019), with a per capita consumption of 109.6 g d^{-1} (Department of Agriculture [DoA], 2021).

Despites its importance, maize production has declined, with an average yield stagnating at 3.6 t ha^{-1} (NSB, 2022) and showing high year-to-year variability (Wangmo, 2024). Maize self-sufficiency has dropped from 99.2% in 2006 to 72.3% in 2019 (DoA, 2021). Factors such as climate variability, labor shortages, human-wildlife conflicts, and a shift to cash crops contributes to reduced maize cultivation. Most notably, changes in temperature and precipitation pose significant threats (Waiba & Sangay, 2024), necessitating an urgent study to assess their impacts on maize production.

Climate variability, including deviations in temperature and rainfall, is a key factor of agricultural performance (Abegaz & Kebede, 2022; Arunrat *et al.*, 2022; Thornton *et al.*, 2014). It leads to extreme weather events, which disrupts ecosystems and livelihoods (Kyaw *et al.*, 2023; Wheeler & Von Braun, 2013). A global trend toward warmer condition is driven by shifts in climate variability (Field *et al.*, 2018). Projections indicate that temperatures in South Asia could rise over by 2ºC by the mid-21st century, with increases of 3-6º C at higher altitudes by the late 21st century (Intergovernmental Panel on Climate Change [IPCC], 2014). Temperature and rainfall variability account for 30–50% of annual cereal yield fluctuations globally (Holleman *et al.*, 2020).

Eastern Bhutan's agriculture, situated on diverse terrains, is highly exposed to climate changes. Historical data (2005-2014) reveal rising summer temperatures and declining winter temperatures, coupled with asymmetrical decreases in annual rainfall, leading to prolonged dry spells during critical crop growth periods (Lhamo *et al.*, 2023; MoAF, 2016; Tenzin *et al.*, 2019). Furthermore, simulation models have revealed notable abnormalities in the distribution and pattern of rain across the country (National Environment Commission [NEC], 2011).

Extreme weather events, including flash floods, windstorm, hailstorm, pest outbreaks, and soil erosion, have significantly impacted Bhutanese farmers (Chhogyel *et al.*, 2020; Katwal *et al.*, 2015; Tenzin *et al.*, 2019; Waiba & Sangay, 2024). For instance, cyclone Aila in 2009 caused extensive damage to crops and infrastructure, while landslides and floods in 2010 affected over 2000 acres of farmland (Tenzin *et al.*, 2019). Soil erosion during the rainy seasons results in the loss of 8.6 tons of soil per hectare annually (DoA, 2011). Prolonged dry spells have also led to crop failures and disrupted planting schedule (Tenzin *et al.*, 2019). Windstorm have caused damage, especially in the pre-monsoon season, affecting over 5000 acres of agricultural crops (maize, rice, potato, chili and buckwheat) in 2010 (DoA, 2010). Warming trend have exacerbated pest and diseases outbreak in maize field (Katwal 2013), contributing to a projected 10.3% decline in maize yields by 2050 under rainfed conditions (International Center for Tropical Agriculture [ICTA], 2017).

Given maize's vulnerability to climate variability, understanding its interactions with climatic factors is crucial. Despites increasing extreme weather events, localized studies on maize production remain limited, leaving the specific impacts unclear. Hence, this study examines time-series data (2006-2023) on precipitation, temperature, and maize yields in eastern Bhutan, using regression models to explore the relationship between climate and crop yield anomalies. Insights from this research will inform strategies to enhance resilience and productivity in maize cultivation.

2 Materials and Method

2.1 Study area

The eastern Bhutan (Lhuentse, Mongar, Tashigang, Tashiyangtse, Pemagatshel and Samdrup Jongkhar) spans 12,942 square kilometres and is home to population of 1.73 million, with a total of 39,938 landholders involved in agriculture (Bureau, 2017). The area experiences diverse climatic conditions, ranging from warm temperate climate in the north to a subtropical climate in the south (Yangdon *et al.*, 2022). Owing to its varied topography, the altitude in the region ranges from 300 to 4000 meter above sea level (masl), with temperature ranging from 15.3^{o} C to 24.6^{o} C and an average annual rainfall of about 1,262 mm (National Center for Hydrology and Meteorology, 2023). Additionally, the region is divided into several agro-ecological zones primarily, subtropical, temperate, and highland, with maize being the predominant crop cultivated at altitudes ranging from 300-3000 masl (Katwal *et al.*, 2015).

Various maize varieties, including open–pollinated and hybrid varieties, are grown in the east, covering approximately 11994 acres of land (NSB, 2022). However, the improved maize variety "Yangtsipa" is the most widely grown due to farmers' preferences and its adaptability (Wangmo, 2018).

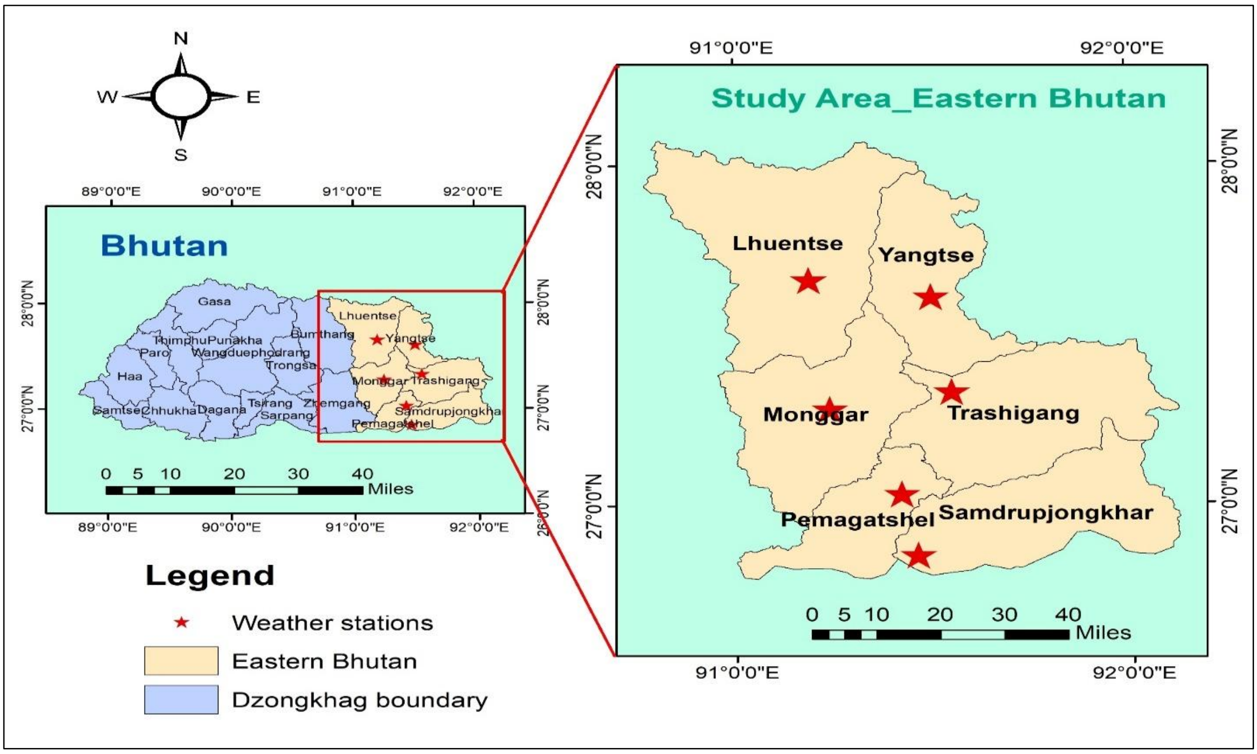

Figure 1. Study area

2.2 Climate and maize anomalies datasets

The research relies mainly on datasets acquired from various government departments and local agencies. Specifically, the time series meteorological data from 2006 to 2023, including precipitation, minimum temperature (T_{min}) and maximum temperature (T_{max}) was acquired from National Centre for Hydrology and Meteorology of the Royal Government of Bhutan. Likewise, the secondary dataset on cultivated area, production, and yield of maize from 2006 to 2023 was obtained from the National Statistics Bureau and the Agriculture Statistics of Department of Agriculture.

2.3 Analysis of Long-term Climate Variability and Trends

The maize growing season in the region spans from March to September and is often considered synonymous with the annual crop cycle. Hence, annual trends for the following climate variables were analysed:

- Temperature (annual maximum and minimum at weather stations of six eastern Districts)
- Precipitation (annual accumulated quantities at weather stations of six eastern districts)
- Area, production and yield of maize annually

The methods used in the paper, including the Mann-Kendall trend test, Sen's slope estimation, Pearson correlation, and multiple linear regression, are appropriate for the study's objectives (Gadedjisso-Tossou *et al.*, 2021; Mann, 1945). The Mann-Kendall test evaluates the presence of trends in a dataset, with the null hypothesis (H_0) stating that no trend exists in the population and the alternate hypothesis (H_1) suggesting the presence of a trend. The null hypothesis is rejected if $p< 0.1$ (Poudel & Shaw, 2016). These statistical methods are widely used in climate variability and agricultural studies to analyse trends and relationships between climate variables and crop production (Yue & Wang, 2004). The computation of the Mann-Kendall test involves specific equations to detect the presence of upward or downward trends in time-series data (Pohlert, 2016), as illustrated below:

$$sgn\ (xi - xj) = \begin{cases} 1, & xi - xj > 0 \\ 0, & xi - xj = 0 \\ -1, & xi - xj < 0 \end{cases} \tag{1}$$

$$E[S] = \sum_{1=1}^{n=1} \sum_{j=i+1}^{n} sgn(xi - xj) \tag{2}$$

$$VAR\ (S) = \frac{1}{18}\{n(n-1)(2n+5) - \sum_{j=1}^{p} tj(tj-1)(2tj+5)\} \tag{3}$$

$$Z = \begin{cases} \frac{E[S]-1}{var\ (s)} & S > 0 \\ 0 & if\ S\ = 0 \\ \frac{E[S]+1}{var\ (s)} & S < 0 \end{cases} \tag{4}$$

In Equations (1) and (2), x_i and x_j represent the value of the time series at a particular position, i and j. S in Equation (2) represents the sum of the signs of the differences between pairs of observations. *"n"* represents the total number of observations in the time series, and t represents the Kendall rank correlation coefficient, which measures the strength and direction of the monotonic trend in the time series.

Similarly, Sen's slope estimator is used to quantify the trend of time series datasets, and it finds application in diverse fields such as hydrology, climatology, and environmental sciences (Meena, 2020; Pohlert, 2016). Sen's slope, developed by Sen in 1968, is a nonparametric procedure used as an index for quantifying trends (Sen, 1968). The slope is calculated using the following equation;

$$\beta = Median\ \left(\frac{xj - xi}{j - i}\right), j > i \tag{5}$$

β represents Sen's estimated slope, $\beta > 0$ means an upward trend, and $\beta < 0$ is a downward trend in a time series. Additionally, *xi* and *xj* are the values of the time series at positions *i* and *j*, respectively, and (*j* - *i*) is the time interval between the two observations.

2.4 Climate-maize anomalies relationship

The Pearson's correlation analysis was performed to measure the strengthen and direction of linear relationship between maize yield and climate variability using following equation;

$$r = \frac{\Sigma((xi - x)(yi - y))}{(\sqrt{(\Sigma((yi - \mathrm{y})^2)})(\sqrt{(\Sigma((yi - \mathrm{y})^2)})} \tag{6}$$

Where, *xi* and *yi* in the equation represent the individual values of the two variables, while *x* and *y* represent the means of the two variables, respectively. The correlation coefficient *(r)* is calculated to assess the statistical significance of the correlation, which can be determined by examining the confidence interval (*p*-value). The range of correlation coefficients is -1 to +1, represents the complete independency of the variables (Poudel & Shaw, 2016). The statistical significance is kept at 95% confidence level. ($p > 0.05$).

Furthermore, to examine causality, a multiple regression analysis was conducted to determine if there is statistically significant difference between independent (rainfall, T_{min}, T_{max}) with dependent variables (maize area, production, yield) as explained by a linear model in the following equations;

$$Y = a + b1\ x1 + b2\ x2 + \cdots bn\ xn \tag{7}$$

Where Y is the dependent variable; *a* is the constant; $b_1, b_2, \ldots, b_n$ are the beta coefficients for independent variables; and $x_1, x_2, \ldots, x_n$ are the independent variables. In these studies, the multivariate regression analysis was carried out separately for maize area, production and yield with precipitation, minimum temperature and maximum temperature as to indicate how climates variables influence the maize attributes.

2.5 Statistical analysis

The descriptive and inferential statistic was performed using statistical software such as R version 4.3.2 and Statistical Tool for Agriculture Research (STAR). For analysing trend of climate and maize anomalies, Mann-Kendall and Sen's slope was used and performed in XLSTAT in Microsoft excel. The significant level in variation of climate trend is considered at $p < 0.05$.

3 Results and discussion

3.1 Descriptive statistics on maize attributes and climate variability

The average area under maize cultivation was 23,894.9 acres, with a deviation of 8,313.3 acres over the years. The lowest area under maize cultivation was recorded at 9,751.2 acres, while the highest was 35,491 acres, suggesting significant year-to-year fluctuations, possibly due to various influential factors. Similarly, the average maize production was 33,868.6 MT, with a standard deviation of 11,438.8 MT, signifying substantial annual variability. The lowest production was 15,415.6 MT, while the highest was 52,950 MT, showing a difference of 37,534.4 MT. Additionally, the average maize yield was 1.5 MT per acre, displaying a moderate fluctuation. The lowest yield recorded was 0.97 MT per acre, while the highest was 1.95 MT per acre, exhibiting a range of 0.98 MT per acre between the best and worst production years, potentially due to growing conditions and management practices (Table 1).

Throughout the study period, the mean temperature was 19.7°C, with fluctuations of approximately 0.5°C (Table 1). The lowest temperature observed was 14.2°C, while the highest reached 25.7°C. The region experiences moderate seasonal or daily temperature changes of around 11.5°C (Table 1). With respect to rainfall, an average of 1418.6 mm was recorded, with deviations of up to 207 mm (Table 1). The highest recorded rainfall was 1841 mm, indicating the occurrence of intense downpours in the region.

Table 1. Descriptive analysis of maize attributes and climate variability

Variables ➛	Maize anomalies			Climate variables			
Descriptive statistic ⤵	Area (Field *et al.*)	Production (MT)	Yield (MT ac^{-1})	Rainfall (mm)	Tmin (° C)	Tmax (° C)	Ave temperature (° C)
Min	9751.2	15415.6	0.9	1025.0	14.2	22.9	18.6
Max	35491.0	52950.0	1.9	1841.8	15.7	25.7	20.3
Mean	23894.9	33868.6	1.5	1418.6	14.8	24.5	19.7
StdDev	8313.4	11438.8	0.2	207.1	0.4	0.8	0.5
SE_Mean	1959.5	2696.5	0.1	48.8	0.1	0.2	0.1
CV (%)	34.8	33.77	18.08	14.6	3.0	3.56	2.8

Min = minimum; Max = Maximum; StdDev = Standard deviation; SE_Mean = Standard error of mean; CV = Coefficient of variance

3.2 Trend of Climate Variability in Eastern Bhutan (between 2006 and 2023)

There was no significant increase for both T_{max} (Kendall's tau = 0.206, p = 0.26, Sen's slope = 0.06) and T_{min} (Kendall's tau = 0.309, p = 0.09, and Sen's slope = 0.03℃/ year) during the last 18 years (2006-2023). However, T_{max} increased by 0.06℃ per year, while T_{min} saw an increment of 0.03° C per year (Fig. 2a). The rate of increase in T_{max} was found to be twice as fast as that of T_{min} (Figure 2a). These findings are consistent with studies of Rinzin *et al.* (2024), which also reported an annual increase in T_{max} ranging from 0.01°C to 0.06° C per year during the season. On the other hand, T_{min} has been steadily rising over time, particularly in 2006, 2011, 2016, 2021, 2022, and 2023 (Figure 2a). The steady increase in both T_{max} and T_{min} is likely attributed to the increase in emission scenario (Rinzin *et al.*, 2024). Additionally, NCHM (2019) has also projected a temperature increase of 0.8- 3.2° C CMIP5 under the RCP 8.5 scenario.

The analysis of annual rainfall trend showed relatively stable throughout the same period, with significant year-to-year variation (Kendall's tau = 0.00, p>0.96, Sen's slope = -5.73 mm per year). Notable fluctuation in rainfall were observed in 2007, 2012, 2019, 2020, and 2022, while decrease was noted in 2006, 2011,2018 and 2021, suggesting that annual rainfall amounts varied without a notable increase or decrease trend in Eastern Bhutan (Figure 2b). This variability may be tributed to interaction of heterogeneous topography (Shrestha *et al.*, 1999) and influence to latitudinal variation (Dorji *et al.*, 2021). Similar finding was reported by Dorji *et al.* (2021), indicating statistically insignificant trends in rainfall for all season. Shahnawaz and Strobl (2015) also observed high variability in monthly precipitation during the rainy season in Bhutan, without a discernible trend in any specific direction of change. Additionally, our results align with those of NCHM (2019), demonstrating significant year-to-year variation in rainfall without any significant increasing or decreasing trend at any weather stations.

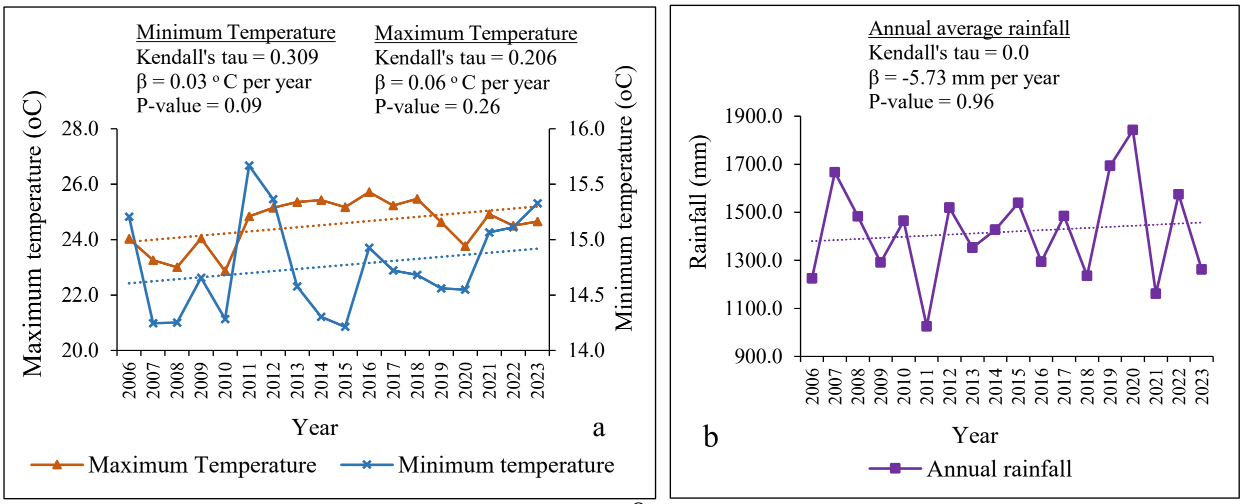

Figure 2. Trend of T_{min} and T_{max} (left) and rainfall (right)

3.3 Trend of Maize area, Production and Yield

A significant decrease in maize area was observed (Kendal's tau = -0.441, β = -1283.5 acres per year, p = 0.013) between 2006 and 2023 as shown in Figure 3. Sen's slope analysis also confirms a yearly decrease of -1,283.5 acres of maize area in the east. The area saw a fluctuation until 2017, however it sharply declined after 2018 (Figure 3). This decline may be ascribed to the reduced number of maize growers, dropping from 38,397 holders in 2021 to 37,707 holders in 2022, representing a 2% decrease (NSB, 2022). There might be several factors behind, however a diagnostic survey could identify factors contributing to the decline in maize area in the east that will aid in revitalizing maize growers.

Likewise, maize production showed a substantial but not statistically significant decline over time (Kendall's tau = -0.206, β = -1043.09 MT per year, p = 0.27) (Figure 3). The Sen's slope estimator confirms a yearly decrease of -1043.09 MT in maize production. This decrease could be associated to crop damage during plant development caused by strong winds, prolonged dry spells, heat waves, damage by wild animals and outbreak of pest and diseases, resulting in significant production losses (NSB, 2022). Further studies are required to quantify these effects.

In contrast, the increase in maize yield was statistically significant (*p* <0.0001) and displayed a positive trend with a Kendall's tau value of at 0.77, suggesting 77% relationship. According to the Sen's slope estimator, maize yield showed an increase of 0.051 metric tons per year, accounting for a 28% increase from 2006 to 2023 (Figure 3). Despites a decrease in maize cultivation area, the increase in annual temperature may have contributed to the rise in maize yield, enabling maize production in higher altitudes. Our findings are consistent with those of Poudel & Shaw (2016), who noted that higher temperatures during the growing season had a positive impact on maize yield in Lamjung District, Nepal. Apart from climate factors, it is possible that agronomic factors, such as access to high-quality seeds, played a role, as 24-50% of maize seed were replaced with seeds of assure high quality through community-based seed production groups (Katwal *et al.*, 2015). As observed, the trend of annual rainfall in the east exhibited a high year-to-year variation but remained relatively stable over the period without significant increase or decrease. Thus, the implementation of dryland irrigation schemes with the support of water reservoirs, sprinklers, drip sets, rainwater harvesting, and the renovation of irrigation schemes (Commercialization Agriculture Resilient Livelihood Enhancement

Program [CARLEP], 2024) may have contributed to the increase in maize yield. Besides, as reported by Poudel & Shaw (2016), the use of new seeds and agricultural technology, improved irrigation, and better crop management practices are also likely to have attributed for the increased crop yield alongside the effect of climate change.

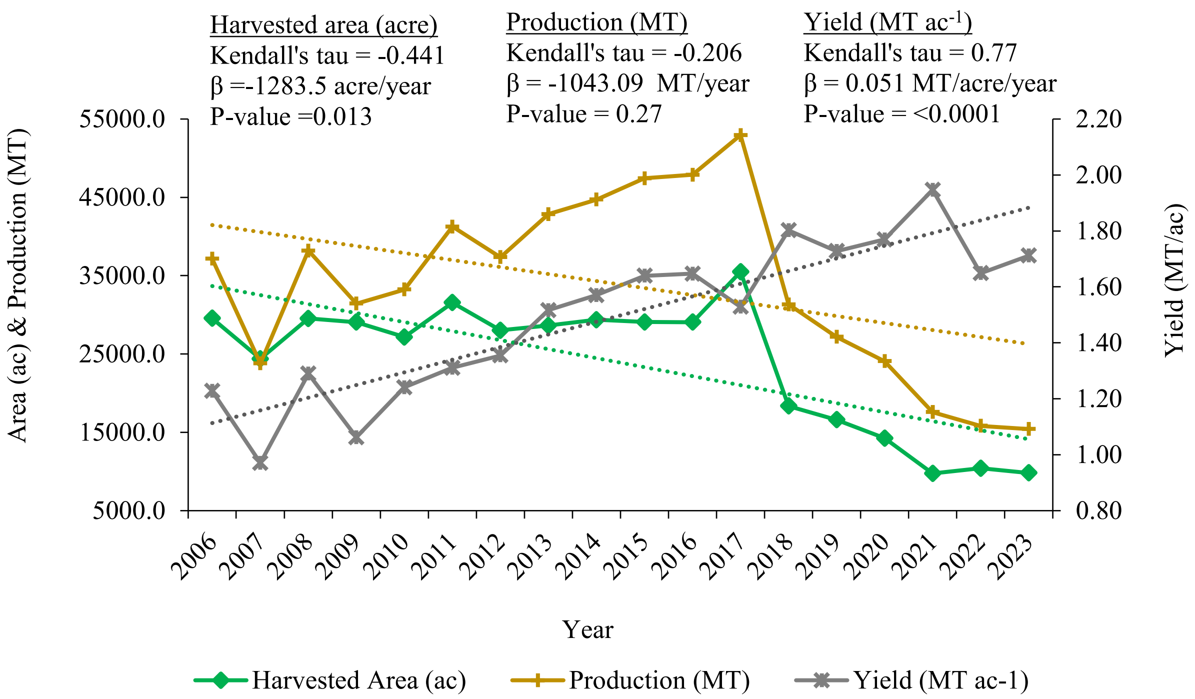

Figure 3. Trend analysis of area, production and yield of maize in Eastern Bhutan

3.4 Correlation between Climate variability (Rainfall and Temperature) and Maize Yield

A weak and negative correlation between rainfall and area (R = -0.15) and production (R = -0.14) was observed, indicating that as rainfall increases, maize production decreases (Table 2). This finding is consistent with the negative correlation between rainfall and rainfed maize in Ethiopia (Moges & Bhat, 2021) and the US Midwest (Liu & Basso, 2020), as well as the result reported in Ghana by Ndamani and Watanabe (2014). However, there was little or no relationship between rainfall and maize yield (p = 0.97; R = -0.009), which aligns with the findings of Poudel & Shaw (2016) regarding the lack of significant effect of rainfall on millet yield in Nepal.

A weak and negative correlation with no significant relationship was found between T_{min}, and maize area (R = -0.19) and production (R = -0.19) (Table 2). Similarly, the association between maize yield and T_{min} was not statistically significant (p = 0.6), although it showed a positive relationship (R = 0.12), implying that maize yield increases with increasing T_{min} (Table 2)

The correlation coefficient between maize production and T_{max} is 0.37, indicating a positive relationship, which suggests that higher T_{max} may be associated with increased maize production (Table 2). However, this correlation is not statistically significant ($p = 0.12$), implying that rising T_{max} does not significantly affect maize production but rather induces the outbreak of pests and diseases, leading to production decline (Escalada *et al.*, 2015). This is supported by incidences such as the fall armyworm outbreak in maize field (Mahat *et al.*, 2021); (Ie *et al.*) and the occurrence of outbreak of turcicum leaf blight, and grey leaf spots, which damaged 70 to 80% maize crop in eastern Bhutan (Katwal *et al.*, 2013). These findings are consistent with studies in Nepal, where the emergence of new pests and diseases has negatively affected crop production over the past 20 years (Maharjan *et al.*, 2009).

Conversely, there was a significant effect of T_{max} ($p = 0.01$) on maize yield, with a coefficient of $R = 0.56$, suggesting a moderate positive relationship between T_{max} and maize yield. This signifies that as T_{max} increases, maize yield tends to increase, and this trend is not correlated with rainfall pattern and T_{min}, but rather with T_{max} (Table 2). The maximum temperature during the study period was approximately 26°C, which is considered optimal for maize growth and development, potentially explaining the observed yield increase over the period. However, if T_{max} continues to rise beyond this range, it could negatively impact maize production, leading to a decline in yields. Developing and adopting heat-tolerant maize varieties could help mitigate the adverse effects of rising temperatures and sustain production levels. These results align with finding indicating increased maize yield being positively associated with higher temperatures in Thailand (Kyaw *et al.*, 2023) and with wheat in Ethiopia (Abegaz & Kebede, 2022). Similar findings also reported in Nepal with positive relationship between T_{max} and wheat yield (Poudel & Shaw, 2016). The increase in maize yield in the eastern region coinciding with rising temperature may be due to non-climatic factors such as agronomic aspects including planting calendar, adoption of improved cultivar fertilizer application, use of certified seeds, and extension services (Atiah *et al.*, 2022; Kyaw *et al.*, 2023; Oluoch *et al.*, 2022).

Table 2. Correlation between climate variables and maize attributes

Climate variables	Coefficient	Area (acre)	Production (MT)	Yield (MT ac^{-1})
Rainfall	R	-0.15	-0.14	-0.009
	p-value	0.53	0.57	0.97
T_{min}	R	-0.19	-0.19	0.12
	p-value	0.43	0.43	0.6

T_{max}	R	0.04	**0.37**	**0.56**
	p-value	0.85	0.12	**0.01**

MT = Metric ton; Tmin = Minimum temperature; Tmax = Maximum temperature

3.5 Changes in maize attributes (area, production and yield) due to climate trend

3.5.1 Climate impact on maize area

The model 1 (Rain only) explained a mere 3% of the variation (R-squared = 0.03) and had an adjusted R-squared of -0.04, signifying poor model fit. The coefficient for rain (-6.29, p = 0.53) was not statistically significant, suggesting a weak or no association between rainfall and maize area (Table 3). The model 2 (Rain and T_{min}) slightly increased the R-squared to 0.14, explaining 14% of the variation in maize area. Nonetheless, the adjusted R-squared remained low (0.03), with neither rain (-15.53, p = 0.21) nor T_{min} (-7691.54, p = 0.17) demonstrating statistical significance (Table 3). In addition, model 3 (Rain, T_{min}, T_{max}) also accounted for 14% of the variation (R-squared = 0.14), but the adjusted R-squared decreased to -0.04. None of the variables, rain (-14.98, p = 0.26), T_{min} (-7933.31, p = 0.18), or T_{max} (585.00, p = 0.73), were statistically significant, suggesting that these climatic factors do not significantly elucidate changes in maize cultivation area (Table 3). Other non-climatic factors, such as farm labor shortages, human-wildlife conflicts, and the replacement of maize cultivation with commercial cash crops, may have contributed to the decline in maize cultivation area.

3.5.2 Climate impact on maize production

Rainfall alone (Model 1) accounts for only 2% of the variation in maize production, and its impact is not statistically significant (p = 0.15). Similarly, the combination of rain and T_{min} in Model 2 explains 13% of the variation, but neither rainfall nor T_{min} shows statistical significance (p > 0.05). In contrast, incorporating rain, T_{min}, and T_{max} in Model 3 explains the highest variation, at 29% (Table 3). Notably, T_{max} has a significant positive impact on maize production (p = 0.03), while rain and T_{min} remain insignificant. This indicates that T_{max} is a key climatic factor influencing maize production, whereas rain and T_{min} have minimal direct effects. The remaining variability (71%) is likely attributable to non-climatic factors, such as the use of high-quality seeds and improved crop management practices.

3.5.3 Climate impact on maize yield

Rain (Model 1) had no significant effect on maize yield (p = 0.98) (Table 3). Although the influence of rain and T_{min} (Model 2) on maize yield was not significant, however they accounted for 3% of the variation (Table 3). The inclusion of rain, T_{min}, and T_{max} (Model 3) provided the best fit, explaining 37% of the variability in maize yield (R-squared = 0.37) (Table

3). T_{max} exhibited a significant positive impact on maize yield (0.19, p = 0.02), whereas rain (0.0003, p = 0.34) and T_{min} (0.04, p = 0.82) showed no significant effects (Table 3). Although T_{max} accounted 37% of the variation in maize yield, 63% of yield changes were still explained by other influential factors. These factors could be the use of quality seeds, better crop management practices and introduction of new agro-technology (Poudel & Shaw, 2016). Similar studies also suggested that types of agronomic practices will have a significant influence on maize yield rather than climate variabilities (Kyaw et al., 2023).

Therefore, T_{max} is the most significant factor, particularly in maize production and yield. Rain and T_{min} exhibited a much weaker influence and did not significantly predict maize outcomes in this study. Any variation or fluctuation in T_{max} will have adverse impact on overall maize production and yield in the region. This result indicates that maize production is highly susceptible to the rising of temperature and there are chances of new pest and diseases outbreak and prolonged dry spell. Thus, the strategies such as introduction of climate resilient varieties need to explored for adapting with the climate change.

Table 3. Impact of different climate predictors on area, production, and yield of maize

Attribute	Model	Predictors	R-squared	Adjusted R-squared	Coefficient of Rain	Coefficient of T_{min}	Coefficient of T_{max}
Area	Model 1	Rain	0.03	-0.04	-6.29 (ns)	-	-
	Model 2	Rain and T_{min}	0.14	0.03	-15.53 (ns)	-7691.54 (ns)	-
	Model 3	Rain, T_{min} and T_{max}	0.14	-0.04	-14.98 (ns)	-7933.31 (ns)	585.00 (ns)
Production	Model 1	Rain	0.02	-0.04	-7.90 (ns)	-	-
	Model 2	Rain and T_{min}	0.13	0.01	-20.28 (ns)	-10310.46 (ns)	-
	Model 3	Rain, T_{min} and T_{max}	0.29	0.15	-14.8 (ns)	-12701.1 (ns)	5784.4 (*)
Yield	Model 1	Rain	0.00006	-0.06	0.0001 (ns)	-	-
	Model 2	Rain and T_{min}	0.03	-0.1	0.0002 (ns)	0.12 (ns)	-
	Model 3	Rain, T_{min} and T_{max}	0.37	0.23	0.0003 (ns)	0.04 (ns)	0.19 (*)

*The p-values are shown in parenthesis; ns = not significant; * = p-value less than 0.05; ** = p-value less than 0.01; *** = p-value less than 0.001; T_{min} = minimum temperature; T_{max} = maximum temperature*

4 Conclusion

The study concludes that rainfall pattern in eastern Bhutan has remained relatively consistent over the study period, with high year-to-year variations. In contrast, neither T_{min} nor T_{max}

demonstrated a significant increase, although rate of T_{max} was observed to be twice as fast as that of T_{min} at 0.06° C per year. Maize, a staple food in the east, experienced a significant decrease in cultivation area and production, as previously discussed. Conversely, maize yield saw a substantial increase of 0.05 metric ton per year, making a 28% increase from 2006 to 2023. Notably, neither rainfall nor T_{min} seemed to have an impact on the area and production of maize in eastern Bhutan, suggesting the presence of other non-climatic factors. However, T_{max} emerged as the influential factor among all climate variables, explaining 29% and 37% variation in production and yield, respectively. Any fluctuation in T_{max} is likely to have a detrimental effect on overall maize production and yield in the region.

Therefore, the study recommends the development of a strategy to mitigate the adverse impact of rising temperatures on maize yield. Furthermore, the declining production cannot be solely attributed to climate variables (rainfall, T_{min}, and T_{max}), indicating the possible influence of other non-climatic factors that should be studied to maximize maize production in the country.

5 Author's contribution statement

Kinzang Thinley and Thinley Gyeltshen were involved in conceptualizing and designing the research protocols, analysing the data, interpreting the results, and drafting the manuscript. Dorji Wangchuk reviewed the manuscript and offered recommendations for further enhancements, while Tshering Pem and Tenzin Rabgay were involved in the formatting and validation of the manuscript. Kinley Sithup, Sonam Deki, and Tshering Choden contributed to sourcing secondary climate data from NHCM, as well as sorting, organizing, and validating the data in an Excel spreadsheet.

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