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# Assessing the Climate Change Impacts on Maize Production in the Slovak Republic and Their Relevance to Sustainability: A Case Study

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**Abstract:** Climate change poses a significant challenge to the agricultural sector, with far-reaching implications on a global scale. As the agriculture sector plays a critical role in the economy of the Slovak Republic, it is crucial to understand the impacts of climate change and, with it, the vulnerabilities that agricultural practices face. Agricultural production and food sustainability are intricately linked to various factors, including population growth and the effects of climate change. This paper focuses on analyzing the production of maize in Slovakia and identifying the factors driving its cultivation. We aim to assess how climate factors influence maize yields across different temperature and precipitation levels through comprehensive data analysis and statistical methods. By utilizing the stochastic production function proposed by Just and Pope (1979) for 1996 to 2022 and estimating model parameters using GRETL software, we aim to provide insights into the relationship between climate change and maize production. Furthermore, we explore the implications of our findings for the sustainability of agricultural practices in Slovakia. Our analysis reveals that the impact of temperature and precipitation on maize yield varies by month and exhibits a nonlinear nature, with climate changes generally exerting a negative influence. Understanding these dynamics is crucial for developing sustainable agricultural strategies that can mitigate the adverse effects of climate change on maize production and ensure long-term food security.

**Keywords:** climate change; maize; yield; temperature; precipitation; price; sustainability

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## 1. Introduction

As agriculture influences climate change and the environment, it is, in turn, affected by these changes and environmental factors. Various factors, such as extreme droughts, floods, greenhouse gases, methane emissions, and many others, impact climate change and the environment. The consequences of agriculture's contribution to climate change, which negatively affects agriculture, are severe [1]. This reality can significantly impact food production and threaten food self-sufficiency and the sustainability of agriculture. Therefore, specific agricultural measures need to be adopted to address this situation. Every country should prioritize adapting its food production systems to cope with and adapt to climate changes, as these are some of the central pressures on agriculture [2].

The constant impact of global warming is called climate change. This term is problematic to define precisely [3] but generally describes a persistent change in climatic parameters over a long period, including factors such as precipitation, temperature, and wind patterns. Climate change also exhibits increased annual weather variability, leading to weather

instability [4]. Climate change signals a significant long-term deviation from expected normal weather conditions in a given region over a specific period. These changes affect the climate and have consequences for various areas within regions. Such changes can persist for decades or even millions of years. Higher temperatures, changes in precipitation, and increased concentrations of $CO_2$ in the atmosphere cause climate fluctuations, as noted by Cheng [5]. Higher temperatures, changes in precipitation, and increased concentrations of $CO_2$ in the atmosphere cause climate fluctuations, as suggested by Cheng [5].

Global climate changes are likely to cause a decline in crop yields in many parts of the world, increasing the need for an adequate selection of more resilient varieties to environmental stresses [6]. For instance, due to global warming, an increase in precipitation and flooding is expected in some regions, which can lead to a reduction in agricultural production. The 2017 study suggests that increased rainfall and poor soil drainage can lead to waterlogging (i.e., when roots are in contact with excess water in the soil) or flooding (when roots and parts or whole shoots are submerged) [7]. Agriculture's response to climate change is particularly sensitive because it depends on climatic conditions. However, climate change impacts on agricultural yields vary between countries and crop types [8].

Additionally, researchers have observed an increasing trend in droughts since 1950, and they expect climate changes to spread and move them northward [9,10]. These transformations are, therefore, expected to have a profound impact on agricultural systems, especially in temperate countries, where water scarcity and increased temperatures present significant constraints on crop production [11]. Both plant and animal agricultural production significantly influence climate change and the environment, which, in turn, dramatically affects these changes.

Climate change presents a double-edged situation for agriculture, particularly crop cultivation. On one hand, it poses a threat due to weather fluctuations that can damage crops and their sustainability [12]. On the other hand, it offers opportunities, enabling farmers to grow crops currently in demand and imported from warmer regions [13].

Slovakia, located in Central Europe, is a landlocked country bordering Austria, the Czech Republic, Hungary, Poland, and Ukraine. The country's landscape is diverse, with the Western Carpathians in the west and north and extensive lowlands in the south. Agricultural land makes up 49.5% of Slovakia's territory. The services, industry, manufacturing, construction, and agriculture sectors support the economy. Slovakia is vulnerable to the effects of climate change, which manifests as extreme weather events like increased precipitation and temperatures, heightening the risk of floods. These climatic impacts also affect key economic sectors, including agriculture [14]. In recent years, the effects of climate change have become increasingly evident, with extreme weather events like increased precipitation and temperatures posing significant risks to agricultural productivity. This study focuses on maize production in Slovakia, a key crop for food and biofuel production.

In Slovakia, the influx of cheaper food after joining the E.U. has led to a decline in the production of vegetables, fruits, and potatoes. However, there has been an increase in the cultivation of cereals and oilseeds, often for biofuel production.

Slovakia experiences varied climatic conditions with significant differences in temperature and precipitation across its regions. Studies indicate that while Northern European countries may benefit from slightly increased temperatures, leading to extended growing seasons and higher yields, Slovakia's continental climate makes it more susceptible to extreme weather events such as unexpected frosts and droughts [3,4]. This variability necessitates a region-specific approach to agricultural planning and development.

Current agricultural policies in Slovakia do not adequately address the unique climatic challenges faced by the sector. There is a need for more flexible and region-specific policies that can adapt to the varying conditions across the country. Recommendations include the development of localized weather prediction models, investment in region-specific research, and the implementation of adaptive technologies tailored to local conditions [10].

Rising air temperatures are associated with an increased capacity of the atmosphere to hold water vapor, leading to more intense rainstorms, even in areas with reduced

precipitation. These changes affect crop production, yield, and quality and contribute to soil degradation processes [15]. As a result, one adverse effect is compounded by another [16].

Overall, climate change tends to cause adverse consequences in the agricultural sector. However, in some cases, such as in Northern European countries, rising temperatures can positively impact crop yields per hectare, especially for crops like wheat and maize [17,18]. In contrast, Sub-Saharan Africa [19,20] and South Asia [21] appear to be the most susceptible to the negative effects of climate change. Increasing air temperatures have already affected the length of the growing season, with cereals maturing and flowering earlier than in the [22].

The physical impacts of climate change on crop yields should evaluated from two temporal perspectives: short-term and long-term. Climate change's short-term impact is similar to climate variability's impact and is generally considered manageable by farmers accustomed to these variable events. On the other hand, the long-term impact raises new concerns, as reactive measures applied solely at the farm level cannot effectively compensate for the persistent reduction in productivity over many seasons. These consequences could be addressed through adjustments in the structure and the entire production system, ensuring access to irrigation infrastructure, and utilizing financial support programs. These measures could help offset lower crop productivity and provide the necessary investment funds [23].

With longer growing seasons and frost-free periods, it would be possible to cultivate new crops that were previously not grown. Conversely, extreme heat and reduced precipitation would lead to decreased productivity. These temperature and vegetation changes could also cause the spread of certain invasive weeds, diseases, and insects, leading to fluctuations in annual crop yields. Implementing farming practices such as crop rotation based on water availability, aligning planting times with precipitation and temperature patterns, and using varieties that better adapt to new conditions can partially mitigate this issue [24].

Some authors found that a higher proportion of intensive management practices on farms leads to increased average crop yields, which is crucial, especially when farmers need to cope with the changing climate and its effects on crop production systems [25]. However, agricultural intensification is a significant cause of ecosystem degradation, particularly soil degradation. Adopting better management practices that steer farmers from excessive fertilizer use can ensure a positive relationship between agriculture and ecology. This approach enhances sustainability by improving soil structure, supporting biodiversity, combating climate change, and promoting long-term environmental health. Sustainable practices such as precision agriculture and organic farming can further bolster soil fertility, conserve water, reduce greenhouse gas emissions, and preserve natural habitats, contributing to a resilient agricultural ecosystem and ensuring food security for future generations.

Global warming is documented worldwide, including in regions like Slovakia, the Czech Republic [26], Poland [27], Austria [28], and Europe [29]. The resulting impact of global warming is called climate change, a phenomenon that is challenging to define precisely [3]. Generally, persistent changes in climate metrics over a long period, including precipitation, temperature, and wind patterns, characterize it. Climate change also manifests as increased year-to-year weather variability, leading to instability.

In general, climate change tends to have adverse effects on the agricultural sector. Nonetheless, in some instances, such as in Northern European countries, rising temperatures positively affect crop yields per hectare [17,18]. For example, the study's authors from 2019 [30] note that the impact of rising temperatures on agricultural yields can be positive and negative, depending on the country's specific characteristics. The effects of climate change on maize yields vary across different regions. Studies show that areas with different climatic patterns experience varied impacts. For instance, research conducted in various areas [31], including China [32] and Sub-Saharan Africa, demonstrates that

climate change affects maize yields differently depending on local climatic conditions and adaptive capacity.

In summary, each component of climate change brings multiple effects, and the prevalence of a specific biophysical impact depends on factors such as soil conditions, plant species, and types.

The primary objective of this study is to address the lacuna in the current literature by investigating the environmental implications of maize cultivation in the Slovak Republic and its association with climate change, with a particular emphasis on sustainability.

Maize was chosen as the object of this study due to its significant representativeness and economic importance in the Slovak Republic. Maize is one of Slovakia's most widely cultivated crops, playing a crucial role in the agricultural sector and the overall economy. Its adaptability to various climatic conditions makes it a suitable crop for studying the impacts of climate variability and change. Additionally, maize is a staple crop with high economic value, making it a critical component of the region's food security and agricultural sustainability. Maize's representativeness is underscored by its extensive cultivation across the country's diverse climatic zones. The crop's sensitivity to temperature and precipitation changes provides a valuable indicator of how climate change might affect agricultural productivity more broadly. This study aims to provide detailed insights into how climate factors influence maize yields, thereby offering a model for similar analyses in other regions.

Further reasons for selecting maize for this analysis include its significant economic impact, as maize contributes significantly to the agricultural economy of Slovakia. It is used for various purposes, including human consumption, animal feed, and biofuel production. Understanding how climate change affects maize yields can help safeguard this vital economic resource. Additionally, maize holds high nutritional value as a major food crop and a key source of calories and nutrients for the population. Analyzing maize production under changing climatic conditions ensures food security and nutritional standards. There is also a substantial body of research on maize, which makes it easier to compare and validate findings. This research background provides a solid foundation for conducting a detailed and rigorous analysis.

One of the unique advantages of maize compared to other crops grown in Slovakia is its particularly high biomass yield. This makes maize exceptionally valuable not only for food and feed but also for bioenergy production. Maize's ability to adapt to various climatic conditions makes it an ideal candidate for studying the broader implications of climate change on agriculture.

The structure of the paper is delineated as follows: it commences with an exposition of the methodologies employed for data collection, followed by the presentation of empirical findings. Subsequently, the paper culminates with a comprehensive discussion of the outcomes, emphasizing sustainable practices and concluding remarks.

## 2. Materials and Methods

This study explores the long-term impact of temperature, precipitation, agricultural land, and sustainable practices on maize production in the Slovak Republic. The dependent variable is maize yield, measured in thousands of tons. Independent input variables include average monthly temperature data in degrees Celsius, total precipitation in millimeters, and market prices in euros per ton during the studied period, with the analyzed timeframe spanning from 1996 to 2022.

The data included in our created database constitute a representative sample of enterprises aggregated at the NUTS3 level, grouped according to the eight regions of the Slovak Republic (Bratislavský, Trnavský, Trenčiansky, Nitriansky, Žilinský, Banskobystrický, Prešovský, Košický). We obtained these data from the databases of the Statistical Office of the Slovak Republic (Definitive Data on the Harvest of Agricultural Crops and Vegetables in Slovakia). They represent the results of processing the Agricultural Census questionnaires conducted by the Statistical Office of the Slovak. These farms engage in agricultural

activities, including managing agricultural land, producing for the market, and primarily focusing on agricultural production.

We obtained historical data on crop production (which is not publicly available) through direct communication with the Statistical Office of the Slovak Republic (ŠÚ S.R.) employees, who provided us with archived databases.

We gathered meteorological variable data from internal records of the Slovak Hydrometeorological Institute (SHMÚ) through data requests.

We based the variable selection on the results of previous studies conducted by many authors [17–19,33–39].

The selection of independent variables in our study was guided by an extensive literature review and the specific climatic and agricultural context of Slovakia. We focused on variables that have been consistently identified as critical determinants of crop yield in previous research. The primary factors considered were temperature and precipitation, given their direct and significant impact on maize growth and productivity. Additionally, we included technological change as a trend variable to account for advancements in agricultural practices and their potential effects on yields.

Numerous studies support our choice of variables. For instance, the studies [19,34] have highlighted the significant influence of temperature and precipitation variability on crop productivity. These climatic factors are known to affect the physiological processes of maize, from germination to maturation, thus directly impacting yields. Furthermore, technological changes and improvements in agricultural practices have been shown to influence crop production, necessitating their inclusion in our model [10].

We employed the stochastic production function model proposed by Just and Pope (1979) to ensure a comprehensive analysis. This model incorporates linear and nonlinear relationships between the independent variables and maize yield. The quadratic terms for temperature and precipitation were included to capture the nonlinear effects observed in previous studies, where extreme values of these variables often lead to yield reductions [18].

In addition to climatic factors, we considered the market price of maize and average precipitation from November to March as independent variables. The inclusion of market price reflects the economic dimension of agricultural production, influencing farmers' planting decisions and resource allocation. The average precipitation from November to March was included to account for soil moisture conditions before the growing season, which can significantly impact subsequent crop yields.

In summary, the independent variables selected for this study are based on established research and their relevance to the Slovak agricultural context. The Just and Pope model further strengthens our analysis by accommodating the complex and nonlinear interactions between these variables and maize yield.

The input database includes crucial data, including total yield, which accounts for the crop production as both primary and secondary, after adjusting for harvest losses and impurities at standard moisture levels according to current standards (STN).

We combined time series data for individual regions of the Slovak Republic into a panel data set, which we subsequently processed and analyzed using appropriate panel methods, building upon the methodology developed by the study's authors from 2021 [40]. The authors examined the Czech Republic similarly, utilizing regional data. This study focuses on the situation in the regions of Slovakia, using data collected for each area.

In our study, the primary analytical framework utilized was the stochastic production function model proposed by Just and Pope (1979). This model is particularly well-suited for analyzing the effects of climatic variables on agricultural production due to its ability to incorporate both linear and nonlinear relationships and account for heteroskedasticity in the data.

However, to ensure the robustness and comprehensiveness of our analysis, we also explored other statistical methods for predicting maize yields. This included multiple linear regression (MLR)

MLR is a straightforward method for understanding the linear relationships between independent variables (such as temperature, precipitation, and technological changes) and the dependent variable (maize yield). This method allowed us to identify the primary factors influencing maize yield and provided a useful benchmark against which we could compare the more complex Just and Pope model.

Thus, we identified the dependencies and existence of meteorological factors' impacts on the production of selected commodities using the stochastic production model proposed by Just and Pope in 1979. This model is a standard method for examining the effects of climate change on agricultural production.

$$\boldsymbol{y} = \boldsymbol{f}(\boldsymbol{X}) + \boldsymbol{h}(\boldsymbol{X})^{\frac{1}{2}}\,\varepsilon \tag{1}$$

here $\boldsymbol{h}(\boldsymbol{X})^{\frac{1}{2}}$ is the predictor function in $\boldsymbol{X}$, $\boldsymbol{y}$ represents yield, and ε is the residual term assumed to be independently and identically distributed (i.i.d.) N(0, δ^2 ε). The Just and Pope specification, especially using this term, provides at least two advantages over the conventional approach. First, it does not consider the risk aspect of production. In other words, when accounting for risk aversion, common on farms, the estimation of the risk effect becomes imprecise. Additionally, the conventional approach often exhibits heteroskedasticity, complicating hypothesis testing regarding the significance of predictors and potentially reducing the efficiency of the model's estimation [41].

The estimation process of Equation (1) involves three steps. First, we performed a regression of $\boldsymbol{y}$ on $\boldsymbol{X}$ s using the ordinary least squares (OLS) method. In the second step, the square roots of the residual values from the first step are regressed on $\boldsymbol{X}$ gain using OLS. Finally, in the third step, $\boldsymbol{y}$ s regressed on $\boldsymbol{X}$ and the square root of the predicted values obtained from the second step.

The model structure in this study, as shown in Equation (2), is formulated as a second-order Taylor approximation that includes environmental variables. This method estimates the nonlinear correlation between crop yield and temperature or precipitation in the respective month. We assume a linear relationship between crop yield, the price index, and moisture. Additionally, the impacts of technological and climatic changes are accounted for by including a trend variable (t). In the case of climatic changes, this trend variable is used with temperature and precipitation variables to capture changes in the first-order parameters caused by climate change effects.

The model can be expressed as:

$$\boldsymbol{y} = \boldsymbol{\alpha}'\boldsymbol{x} + \boldsymbol{\beta}'\boldsymbol{y} + \boldsymbol{\gamma}'\boldsymbol{x^2} + \boldsymbol{\delta}'\boldsymbol{z} + \boldsymbol{h}(\boldsymbol{X})^{\frac{1}{2}}\,\varepsilon \tag{2}$$

where $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$ represent the vector parameters to be estimated, and $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ denote the vectors of regressors. These regressor vectors $\boldsymbol{x}$, $\boldsymbol{y}$, and $\boldsymbol{z}$ are composed of the following variables (with the variables being logarithmically transformed and normalized to their mean values):

$\boldsymbol{x}$**:**

- P_index_ratio—(lPP)—maise price in euro per ton.
- Moisture—(Mo)—the average precipitation from November to March.

$\boldsymbol{y}$**:**

- Monthly temperatures—(t4,. . ., t7)—mean temperatures from April to July.
- Monthly precipitation—(p4,. . ., p7)—means precipitation from April to July.

$\boldsymbol{z}$**:**

- Climate change variables—(t4t,. . . t7t, p4t,. . ., p7t)—mean monthly temperatures and precipitation combined with the time vector.
- Time vector—(t and t_2)—represents technological change.

The model parameters were estimated using GRETL software version 2021d. Our study used the GRETL software to make predictions and perform statistical analysis.

GRETL (Gnu Regression, Econometrics, and Time-series Library) is an open-source software package for econometric analysis. It provides a wide range of functionalities for data manipulation, model estimation, and hypothesis testing, making it well-suited for the comprehensive analysis required in this research. The software allowed us to effectively implement the stochastic production function model proposed by Just and Pope (1979). Using GRETL, we handled the panel data structure, estimated the model parameters, and performed the necessary regressions to capture the complex relationships between climatic variables and maize yield.

Due to the nature of panel data, this was possible only by applying the fixed effects model. This approach allows for different interpretations for each cross-sectional unit, in this case, the regions of Slovakia. It assumes the slope coefficients are the same across all regions, but the intercepts vary. In the literature, this model is known as the Least Squares Dummy Variable (LSDV) model.

## 3. Results

To interpret the study's output results, we used box plot graphs to capture the average monthly temperatures and average monthly precipitation totals for each region of Slovakia from 1996 to 2022. Box plot graphs let us visually present temperature and precipitation data, providing summary statistical information such as minimum and maximum values. This approach enabled comparison of temperature and precipitation distributions across different time points and regions. In cases where some values deviate significantly, we exclude them from selecting maximum and minimum values and display them as isolated points above the minimum or maximum.

The following image (Figure 1) shows the captured average lowest and highest temperatures for January, February, and March. The lowest temperature during the observed period was in January, at 9.72 °C in the Banská Bystrica region in 2017. Conversely, the highest temperature in January was recorded in the same region in 2007, at 5.16 °C. In February, the lowest temperature was −7.27 °C in the Prešov region in 2012, while the highest was 6.15 °C in the Bratislava region. In March, the lowest temperature was −0.52 °C in the first observed year in the Prešov region, and the highest temperature in March was recorded in the Bratislava region in 2017, at 9.59 °C.

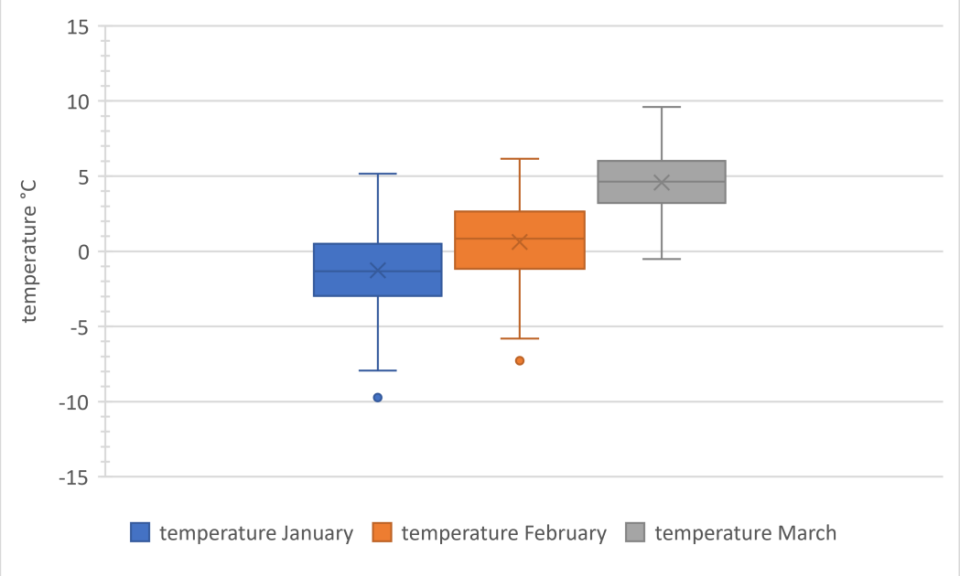



**Figure 1.** Average Temperatures for January, February, March (1996−2022). Source: Own processing according to SHMÚ.

We observe the following values for minimum and maximum average temperatures in April, May, and June. In April, the lowest average temperature was recorded in the Žilina

region in 1997 (4.77 °C), while the highest was 16.21 °C in the Nitra region in May 2016. In May, the Prešov region recorded the lowest temperature of 11.28 °C in 1997, while the Nitra region observed the highest temperature of 19.75 °C in 2018. The last month recorded in Figure 2 is June, when the lowest measured temperature was 14.58 °C in the Žilina region (2001), and the highest reached nearly 24 °C in the Bratislava region (2019).

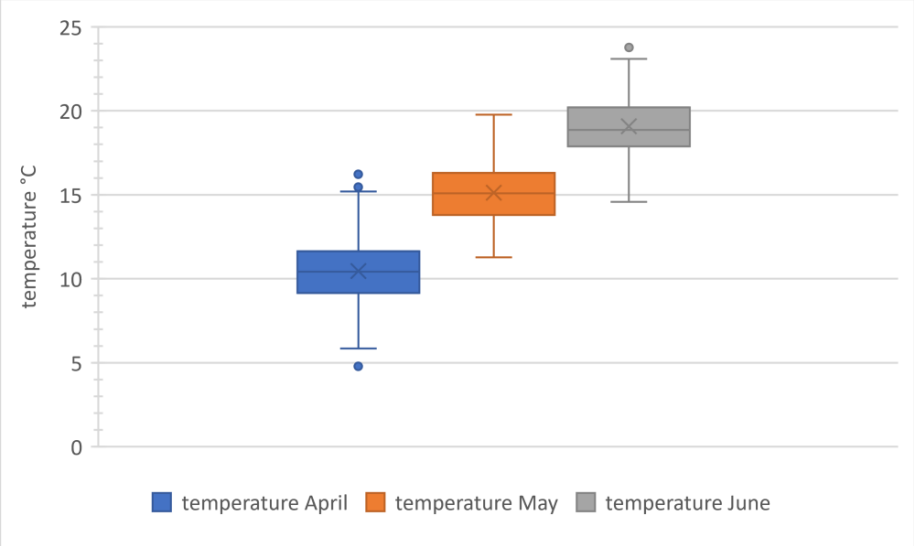



**Figure 2.** Average Temperatures for April, May, June (1996−2022). Source: Own processing according to SHMÚ.

The upcoming image (Figure 3) shows the average temperatures for the next three months (July, August, and September) with the following data. The lowest recorded temperature during July in the observed period was 15.44 °C in the Žilina region in 1997, according to SHMÚ data, while the highest temperature in July was 24.64 °C in the Bratislava region in 2006. In August, the coldest temperature was 16.09 °C in the Žilina region in 2006, and the highest recorded temperature was 24.06 °C in the Nitra region in 2021. September was the coldest in 1996 (Žilina region, 9.88 °C), and the warmest temperature during September was 18.73 °C in the Nitra region in 1999.

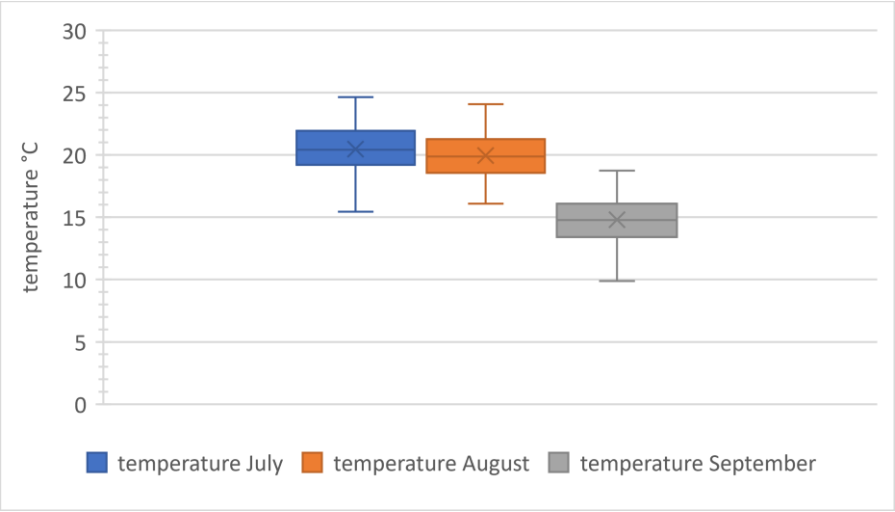



**Figure 3.** Average Temperatures for July, August, September (1996−2022). Source: Own processing according to SHMÚ.

Figure 4 shows the last three observed months (October, November, December). October was the coldest (4.95 °C) in the Prešov region in 2010, while the highest temperature was recorded in 2000 in the Nitra region, reaching 13.81 °C. In November, the lowest temperature was 0.03 °C in the Žilina region in 1998, and the warmest November was in the Nitra region in 2019 (8.86 °C). In the final observed month, December, the lowest recorded temperature was −7.08 °C in the Banská Bystrica region (2001), and the highest was 4.01 °C in the Nitra region in 2020.

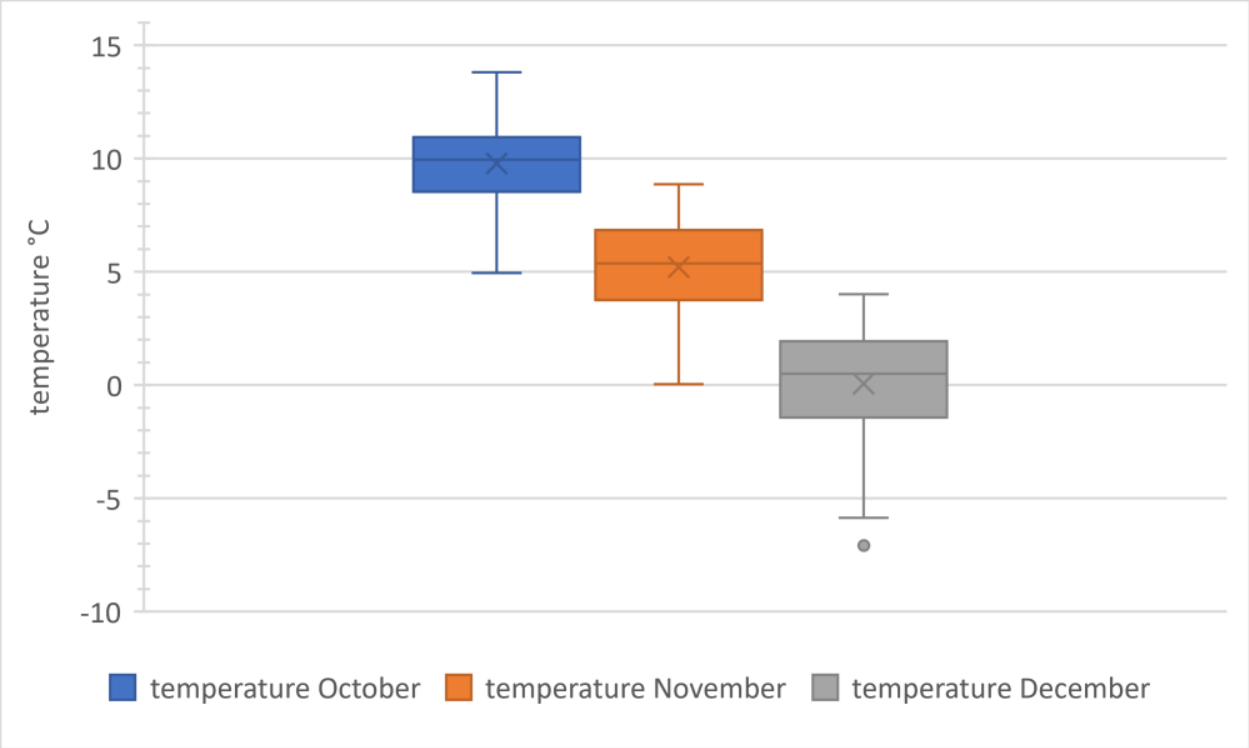



**Figure 4.** Average Temperatures for October, November, December (1996−2022). Source: Own processing according to SHMÚ.

Similarly, through graphical representation (box plot graphs), we also illustrate the average highest and lowest precipitation totals during the months for each region of Slovakia over the period 1996–2022 (Figure 5). The lowest precipitation total in January was recorded in 2002 in the Košice region (5.19 mm), while the highest precipitation was in the Banská Bystrica region in 2013 (131 mm). The Banská Bystrica region also had the lowest precipitation in February, specifically 0.1 mm, and the highest precipitation in 2016, reaching 129.6 mm. March was the least rainy in 2003 in the Trnava region (0.8 mm), with the highest precipitation recorded at 122.59 mm in the Nitra region in 2013.

Figure 6 shows that, in April 2007, no precipitation was recorded in the Banská Bystrica region, while up to 132.3 mm of rain fell in the Žilina region in 2017. The least rainy May was the last observed year in the Košice region (9.5 mm), whereas the highest precipitation was recorded in 2010 in the Žilina region, with a total of 215.9 mm. In June, the lowest precipitation total was 4.7 mm in the Nitra region (2000), and the highest was 292.6 mm in the Trenčín region (1999).

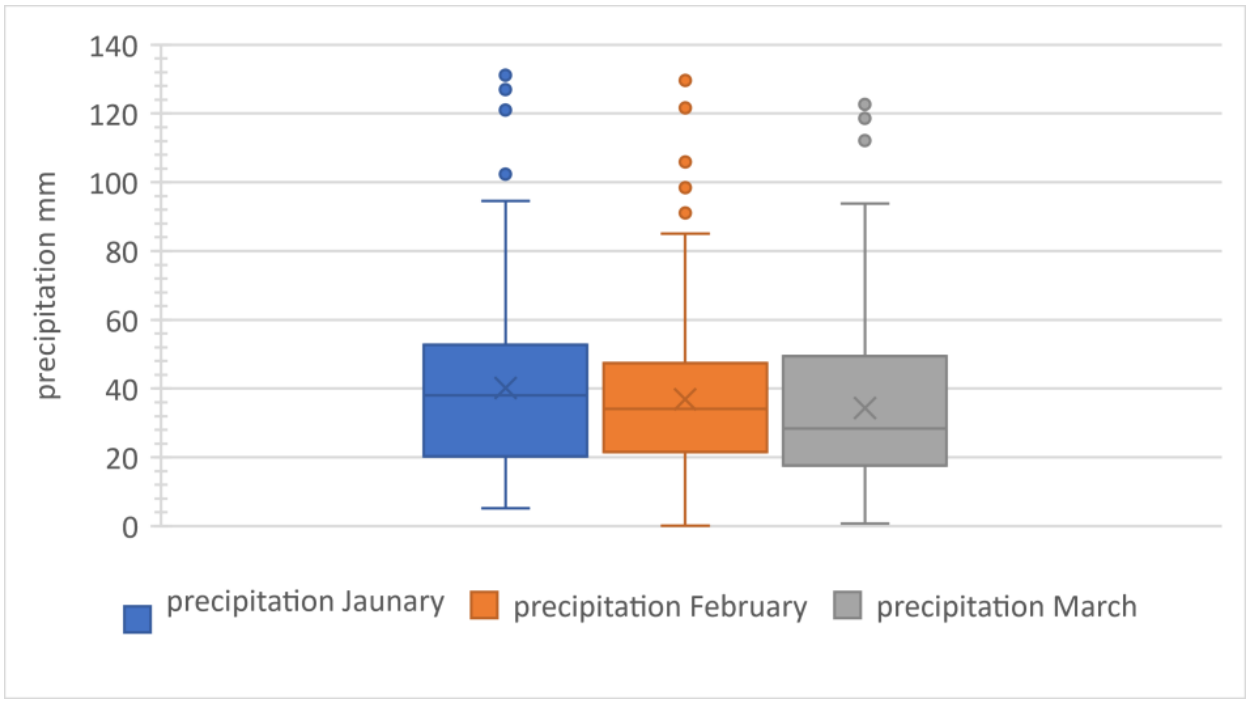



**Figure 5.** Average Precipitation Totals for January, February, March (1996−2022). Source: Own processing according to SHMÚ.

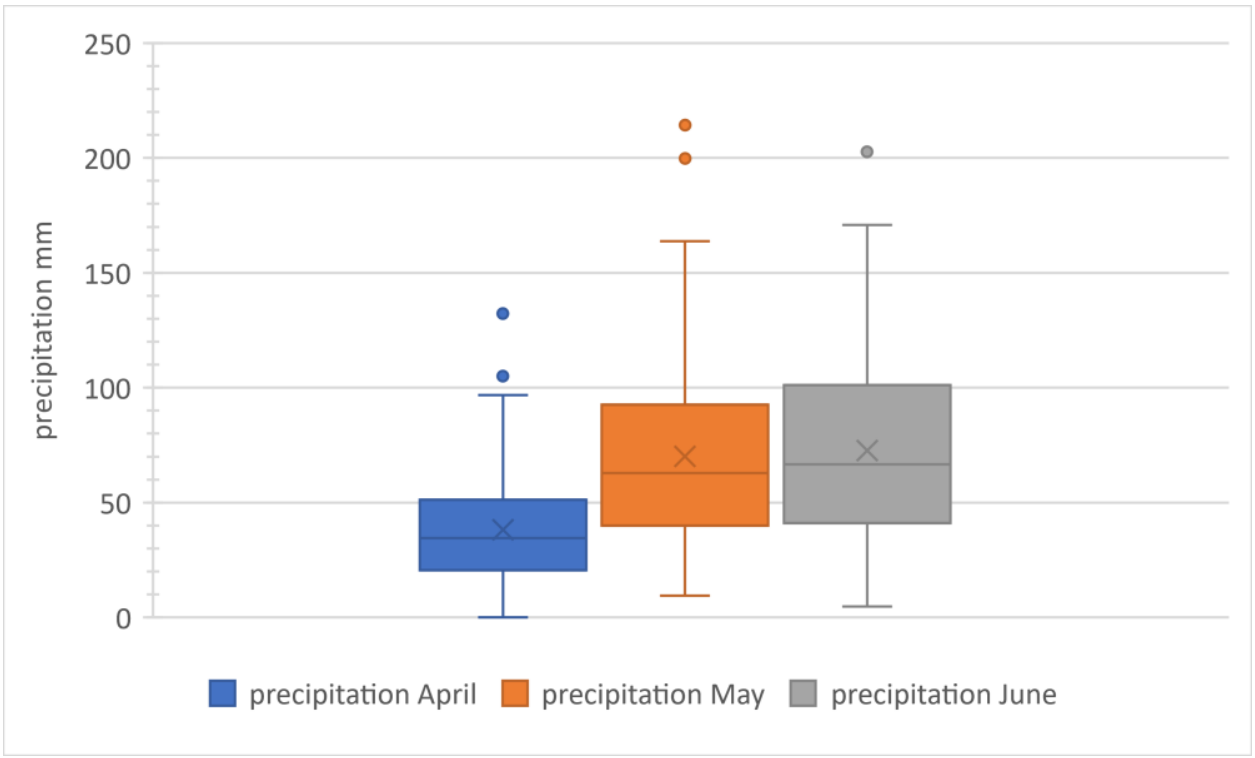



**Figure 6.** Average Precipitation Totals for April, May, June (1996−2022). Source: Own processing according to SHMÚ.

The following image (Figure 7) presents the average precipitation totals for July, August, and September. Analysis indicates that the Trnava region had the lowest average

precipitation of 5.5 mm in July 2013, while the Žilina region recorded the highest total in 2001. In August, the lowest average precipitation total was 4.6 mm in the Trenčín region in 2003, whereas the highest total was recorded in the Žilina region in 2021, reaching 224.9 mm. In September, the highest average precipitation total was 184.7 mm in the Trnava region in 2018, while the lowest was −1 mm in the Trenčín region in 2015.

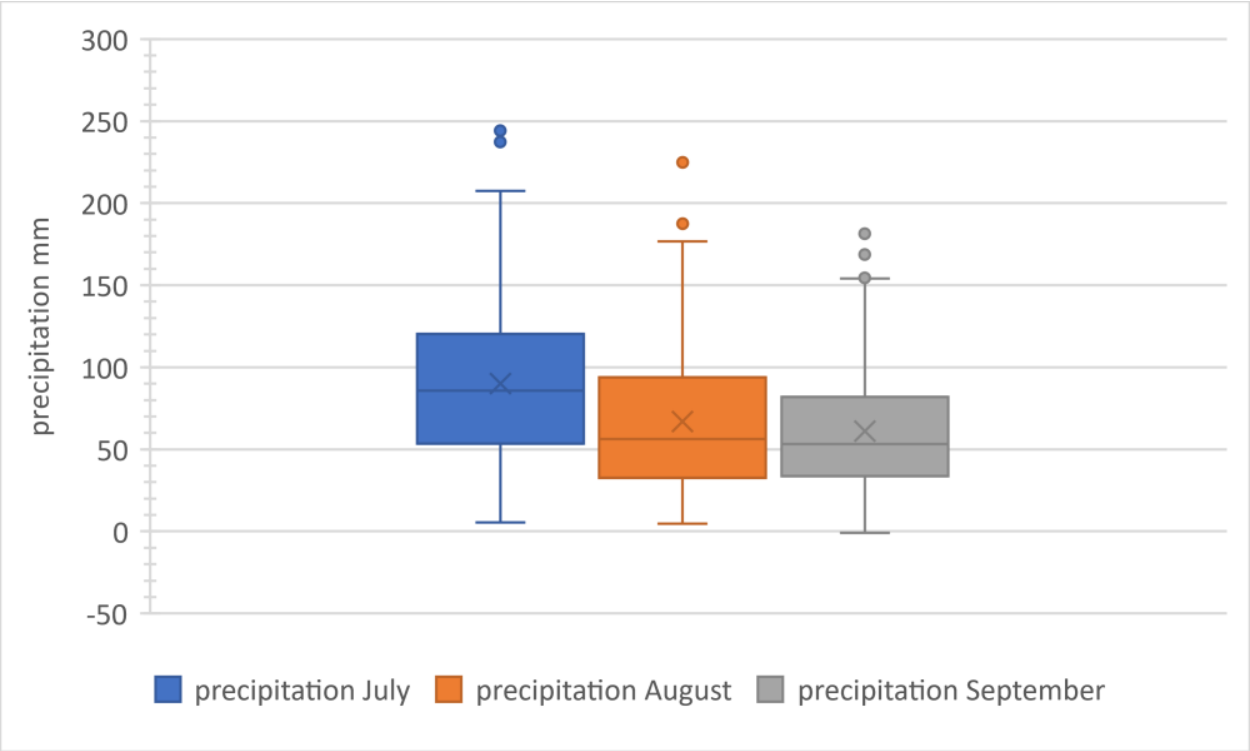



**Figure 7.** Average Precipitation Totals for July, August, September (1996–2022). Source: Own processing according to SHMÚ.

The last analyzed months for precipitation totals were October, November, and December illustrated in Figure 8. In October, we identified the minimum precipitation total in the Trenčín region in 2015, which reached 1 mm, while the highest total was recorded in the Bratislava region in 2014, at 154.89 mm. In November, the precipitation total in the Bratislava region in 2011 was zero, whereas the highest total was recorded in the same region in 2010, reaching 131.2 mm. In December, we observed the minimum precipitation total in the Nitra region in 2006, which reached 4.9 mm, while the highest total was recorded in the Banská Bystrica region in 2009, at 136.7 mm.

The subject of this study is the analysis of results from the Just and Pope model, which provides a comprehensive view of the complex relationships between various variables affecting the production of selected crops. We standardized the data before conducting the regression analysis to ensure accurate comparisons, considering that not all independent variables were measured in the same units. According to the theory by Hálová et al. (2021) [41], the relationship between temperature and precipitation to yield is not linear. Hence, the model includes quadratic forms of temperature and precipitation.

The crop we focused on from the cereal category is maize. Our analysis provides comprehensive results on how the yield of this important crop changes in response to climatic conditions. Maise is one of the most crucial crops globally, and its production is vital for food self-sufficiency and economic stability.

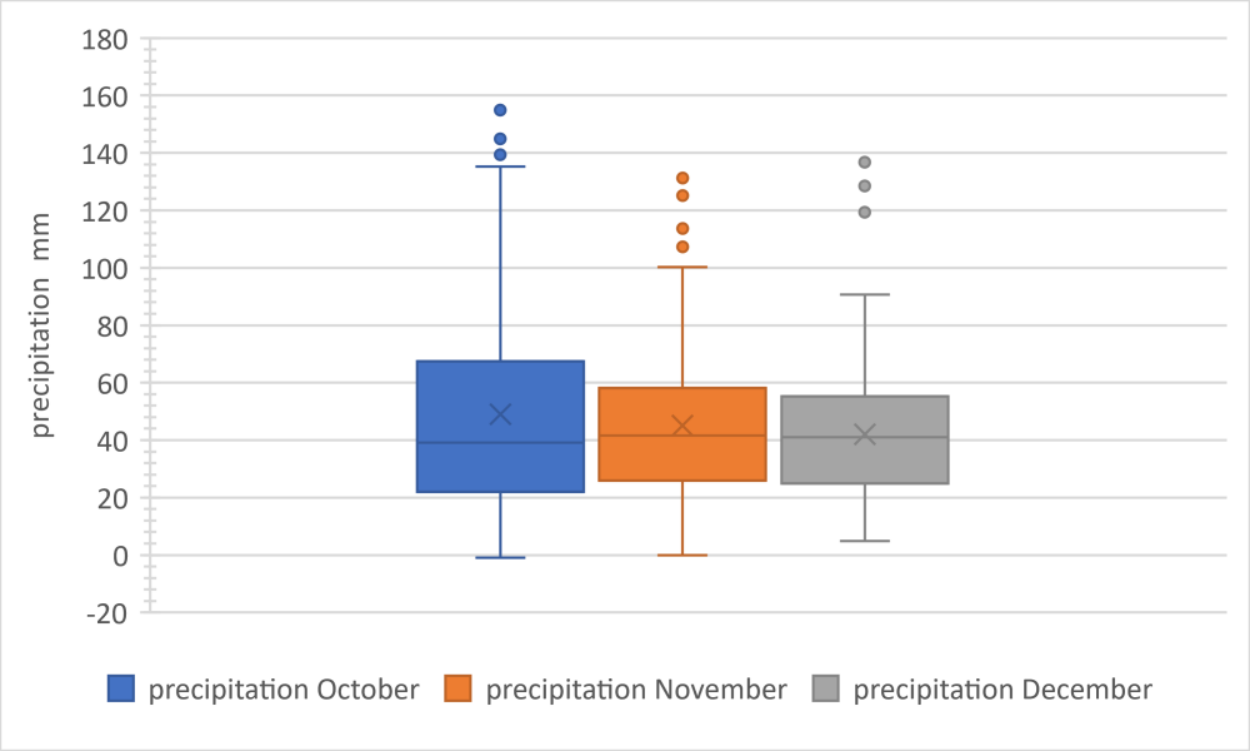



**Figure 8.** Average Precipitation Totals for October, November, December (1996−2022). Source: Own processing according to SHMÚ.

Table 1 contains the coefficient estimates, standard errors, t-ratios, and *p*-values for various variables in the model. The variables include the price of maize (Price), average monthly precipitation (Mo), as well as average monthly temperatures (t4, t5, t6, t7) and average precipitation (p4, p7) for specific months. The combined variables (t5t, t6t, t7t, p4t, p5t, p6t, p7t) include interactions between temperature and precipitation, along with their quadratic terms (t5t_2, t6t_2, t7t_2, p4t_2, p7t_2). The last two rows of the table show the coefficients for the time vector (t, t_2), representing technological progress over time. The *p*-value determines the statistical significance of each coefficient. These symbols indicate significance levels: *** for $\alpha = 0.01$, ** for $\alpha = 0.05$, * for $\alpha = 0.1$. Coefficients that are statistically significant at these levels are marked with the corresponding number of asterisks. The table presents the study's results on the impact of climate change (temperature, precipitation) on maize production and its variability.

The model met all required assumptions. When interpreting the results, it is essential to note that the values are generalized for the entire territory of the Slovak Republic. The estimated values can be considered average trends for Slovakia. This approach has the advantages of reduced variability of estimates and the ability to include multiple explanatory variables. However, the drawback is that many independent variables made estimating differences between regions in the slope coefficients impossible.

The estimated parameters can be interpreted as elasticities, meaning they measure the percentage change in the dependent variable caused by a 1% change in the independent variables. The negative relationship between price and maize yield is based on the expectation that higher prices reflect market expectations of lower maize yields.

We observed a statistically significant effect of the market price for maize, which was linear and negative. This finding is consistent with expectations, as a higher market price is associated with lower maize yields, likely due to market expectations of reduced yields. Conversely, with increasing yields, we can expect lower market prices. The lowest recorded maize yield in the Bratislava region was in the last observed year, at 3.93 t/ha, with the

price reaching €265.86 per ton. The lowest price for this grain was €87.76 per ton, with a yield of 7.4 t/ha in the Bratislava region in 2009.

**Table 1.** Estimated parameters of stochastic production function—mean equation.

| Maise | Coefficient | Std. Error | t-Ratio | *p*-Value | Significance |
|---|---|---|---|---|---|
| Const | −1.343 | 1.607 | −0.836 | 0.405 | |
| Price | −0.338 | 0.068 | −4.958 | 0.000 | *** |
| T4 | −0.806 | 0.346 | −2.326 | 0.021 | ** |
| T5 | 1.143 | 0.733 | 1.559 | 0.121 | |
| T6 | 1.750 | 0.883 | 1.983 | 0.049 | ** |
| T7 | 2.222 | 0.956 | 2.323 | 0.021 | ** |
| T4_2 | 0.776 | 0.353 | 2.201 | 0.029 | ** |
| T5_2 | −1.246 | 0.716 | −1.740 | 0.084 | * |
| T6_2 | −1.822 | 0.949 | −1.920 | 0.056 | * |
| T7_2 | −2.454 | 1.011 | −2.428 | 0.016 | ** |
| Mo | −0.197 | 0.074 | −2.654 | 0.009 | *** |
| P4 | 0.501 | 0.172 | 2.913 | 0.004 | *** |
| P5 | 0.234 | 0.156 | 1.502 | 0.135 | |
| P6 | 0.290 | 0.168 | 1.718 | 0.088 | * |
| P7 | 0.217 | 0.174 | 1.246 | 0.214 | |
| P4_2 | −0.299 | 0.126 | −2.372 | 0.019 | ** |
| P5_2 | −0.337 | 0.147 | −2.300 | 0.023 | ** |
| P6_2 | −0.155 | 0.155 | −1.000 | 0.319 | |
| P7_2 | −0.136 | 0.165 | −0.822 | 0.412 | |
| T4_t | 0.374 | 0.293 | 1.275 | 0.204 | |
| T5_t | −0.493 | 0.524 | −0.942 | 0.348 | |
| T6_t | 0.584 | 1.007 | 0.580 | 0.563 | |
| T7_t | −0.068 | 0.961 | −0.071 | 0.944 | |
| P4_t | 0.074 | 0.074 | 1.000 | 0.319 | |
| P5_t | 0.206 | 0.068 | 3.048 | 0.003 | *** |
| P6_t | −0.068 | 0.068 | −1.012 | 0.313 | |
| P7_t | −0.118 | 0.116 | −1.014 | 0.312 | |
| t | 0.149 | 0.113 | 1.324 | 0.187 | |
| t_2 | −0.003 | 0.001 | −2.010 | 0.046 | ** |

*** significant at $\alpha = 0.01$ ** at $\alpha = 0.05$ * at $\alpha = 0.1$. Abbreviations: **Const**: Constant term, **Price**: Market price of maize, **T4–T7**: Temperature in April, May, June, July, **T4_2–T7_2**: Quadratic term for T4, T5, T6, T7, **Mo**: Average precipitation from November to March, **P4–P7**: Precipitation in April, May, June, July, **P4_2–P7_2**: Quadratic term for P4, P5, P6, P7, **T4_t–T7_t**: Interaction term of T4, T5, T6, T7 and time, **P4_t–P7_t**: Interaction term of P4, P5, P6, P7 and time, **t**: Time trend, **t_2**: Quadratic term for time trend. Source: own processing.

A study [42] in Ethiopia analyzed the impact of price shocks on maize markets and found that increased prices are often associated with lower yields. Higher prices reflect market expectations of reduced yields, leading to decreased availability and higher input costs, subsequently lowering production. Similarly, a study [43] examined the adoption of hybrid maize varieties and their impact on farmers' economics. They found that higher production costs for hybrid maize (due to more expensive seeds) lead to higher market

prices, which may discourage farmers from investing in production in the case of expected lower yields.

A statistically significant impact of temperature from April to July was found. The quadratic relationship indicates that yields depend on optimal temperatures during all four months. Temperatures must not be below average or above average. Maise goes through a series of growth phases during April, May, June, and July that are critical for its development and productivity. After the seeds are sown in April, maize undergoes germination and begins to root. In May, the growth process intensifies, with maize developing stems and leaves and entering the flowering phase. June is characterized by continued growth and the beginning of ear formation. In July, maize reaches the critical phase of ear development and maturation.

Given these growth phases, we can confirm the significance of temperature from April to July for maize yield based on our statistically significant variables (temperature from April–July). This period is crucial for the final crop yield. The nonlinear positive impact of April temperatures on maize production, represented by the coefficient T4_2: 0.776 with a *p*-value of 0.029, indicates that the effect of temperature on maize production in April changes nonlinearly. Specifically, this positive nonlinear coefficient for the quadratic term of temperature suggests that maize production initially decreases and then increases as April temperatures rise. We identified nonlinear relationships between temperature and maize yields. A slight temperature increase can positively affect yield, while extremely high temperatures are detrimental.

The article from 2012 [34] also confirms nonlinear relationships, where temperature and precipitation extremes negatively impact crop production, consistent with our findings on the quadratic effects of temperature and precipitation. At lower temperatures in April, an increase in temperature can initially harm maize production (causing plant stress or creating unsuitable growth conditions). However, at higher temperatures in April, after exceeding a certain threshold, further temperature increases begin to positively impact production (creating more suitable conditions for maize growth and maturation).

A review published by authors from 2023 [31] found that with each one °C increase in temperature, global maize yields decrease by an average of 7.4%. It aligns with our findings, which show that higher temperatures reduce maize yields in Central Europe due to accelerated plant development and shortened grain-filling periods. The negative coefficients (T5_2, T6_2, T7_2) indicate that as temperatures increase in May, June, and July, maize production may initially rise, but after reaching a certain level, the impact becomes negative. It means that very high temperatures during these months significantly reduce maize production. Based on our findings, the average temperatures in these months range from 9.8 °C to 22.0 °C.

The quadratic relationship of precipitation in April and May was also confirmed to be statistically significant. During these periods, precipitation should be optimal—not too high nor too low. A moderate soil moisture level positively affects thermal conditions, benefiting root system growth and ensuring better nutrient absorption. However, after reaching a certain amount, further increases in precipitation start to negatively impact production. Excessive precipitation can lead to soil waterlogging, damaging plant roots, reducing oxygen availability, and promoting mold growth and diseases. Research on maize production in China [32] noted significant impacts of precipitation variability on maize output. Consistent with our findings, increased precipitation variability, including drought and excessive precipitation, can negatively affect maize growth. Research [44] in the North China Plain (NCP) also demonstrated that extreme weather events, such as droughts and floods, significantly reduce maize yields. The average precipitation in April ranged from 30.9 mm to 45.1 mm, with higher precipitation above this average leading to lower yields. In May, the average precipitation during the observed period ranged from 55.8 mm to 86.5 mm, with similar trends observed regarding optimal precipitation levels for maize yield.

A linear negative relationship between average precipitation from November to March was also confirmed. This effect is statistically significant at the $\alpha = 0.01$ level, meaning that with 99% confidence, we can assert that the observed relationship is not due to chance but exists. From November to March, the soil prepares for the upcoming growing season. Precipitation must remain within an optimal range to maintain proper soil moisture, essential for preserving ideal conditions for the subsequent maize growing season. If the soil is too dry, it leads to a lack of moisture, potentially affecting future maize yields.

Increased precipitation from November to March has a negative effect on maize production. It indicates that excessive precipitation during these months can reduce maize yields. Excessive precipitation causes soil waterlogging, negatively affecting maize growth and crop quality. As monthly precipitation increases, maize production decreases. Authors [45] studied the impact of precipitation during the growing season on maize yields in the eastern United States. They found that increasing precipitation variability, especially during the winter and spring, can negatively affect maize yields. Their results indicated that excessive precipitation during these months leads to soil waterlogging issues.

Other authors [46] also confirmed this negative relationship and used the APSIM-Maize simulation model to comprehensively analyze agronomic and climatic data. The study's results showed that increased precipitation combined with low temperatures during the winter period significantly negatively impacts maize production. This effect occurs due to soil waterlogging, which disrupts the plant's root system and reduces its ability to absorb nutrients. This ultimately decreases overall yields. Therefore, the precipitation during these months must be adequate to achieve suitable soil moisture. Average precipitation during these months ranged from 32.1 to 43.8 mm. Scientific papers have reported [34,47] also found that increased temperatures and precipitation variability reduce maize yields. Our findings are consistent with these studies, indicating that extreme temperatures and irregular precipitation can negatively affect crop yields.

Based on the analysis of long-term trends, we confirm that climate change, specifically precipitations in May, influences maize production. The analysis of long-term data (1996–2022) suggests that an increase in precipitations in this month leads to higher production. The significant positive impact of the interaction between the time variable and May precipitations (P5_t) indicates that the influence of May precipitations on maize production improves over time. This trend highlights the importance of May precipitations for maize yield and its impact on agricultural production. A study from 2018 [48] investigated the impact of climatic variables on crop yields in the Great Plains region of the United States and found, similarly to our study, that May precipitations are a crucial factor influencing yields. Specifically in Kansas and Oklahoma, May precipitations were the primary factor explaining differences in crop yields. In Kansas, yield differences were significantly influenced by May precipitations with a high coefficient of determination ($r^2 = 0.78$), indicating a strong correlation between May precipitations and yields. Increased precipitation during the growing season (including May) positively affects crop production [49]. May precipitation provides the necessary moisture for optimal crop growth, leading to higher yields.

Our analysis reveals significant regional differences within Slovakia that must be considered when developing agricultural strategies. For instance, the Trnava region has experienced lower average precipitation in critical growing months compared to the Žilina region, which affects crop yields and farming practices [11]. These findings suggest that localized data and tailored strategies are essential for effective agricultural management in Slovakia.

## 4. Discussion

This study aimed to analyze the long-term impact of temperature and precipitation on maize production in Slovakia using the stochastic production model proposed by Just and Pope. This model, introduced in 1979, is widely recognized as a standard tool for examining the effects of climate change on agricultural production. Thanks to its ability to model and

understand the complex interactions between climate variables and crop performance, it provides robust frameworks for analyzing the influence of temperature, precipitation, and other factors on crop production, thereby enhancing our understanding of the dynamics of the agricultural system in the context of climate change. The results of our analysis indicate that climatic factors, such as temperature and precipitation, significantly influence maize yields. We analyzed standardized data by employing the Just and Pope model, allowing us to identify critical relationships between climatic variables and agricultural productivity. Our analysis demonstrated that temperature extremes and precipitation variability negatively impact maize yields, consistent with other studies showing that temperatures above optimal values and irregular precipitation can substantially reduce crop productivity [18,19,34]. Specifically, we found that temperature in April has a negative effect on maize yields (T4), while temperatures in June and July have positive effects (T6 and T7). Quadratic terms highlight nonlinear relationships between temperature and maize yields. High temperatures beyond a certain threshold can reduce yields, as evidenced by the T5_2, T6_2, and T7_2 coefficients. Monthly precipitation in April (P4) positively impacts yields, while precipitation from November to March (Mo) has a negative impact. Quadratic terms for precipitation in April and May (P4_2 and P5_2) also indicate nonlinear relationships, where excessive precipitation can lead to yield reductions [44,45]. Technological changes and their impact on yields are accounted for by the trend variable (t_2), which suggests an adverse effect of technological changes (coefficient −0.003), likely due to inadequate adaptation of technologies to changing climatic conditions. The positive impact of the interaction between the time variable and precipitation in May (P5_t) suggests that the effect of May precipitation on production improves over time [10].

Our findings align with other international studies. For instance, the study [34] found that rising temperatures generally lead to a reduction in crop yields due to accelerated crop development and shorter grain-filling periods. This is consistent with our findings on the negative impact of temperature extremes. Similarly, the study [19] reported that increasing temperature and precipitation variability pose significant threats to maize yields in Sub-Saharan Africa, emphasizing the need for adaptive strategies. In temperate regions, the study [18] observed that moderate increases in temperature could positively affect crop yields, but extreme temperatures are universally detrimental. This aligns with our findings on the nonlinear effects of temperature on maize yields in Slovakia. King, in his study [17], showed that rising temperatures in Northern Europe might extend the growing season but also increase the risk of heat stress and water scarcity, negatively affecting crop yields. Research conducted in the United States by Huang et al. (2015) found that excessive precipitation during critical growing periods can lead to reduced maize yields due to waterlogging and associated plant stress. Similarly, the study [44] identified significant impacts of precipitation variability on maize output in China, noting that both drought and excessive rainfall negatively affect maize production. These studies corroborate our findings on the importance of optimal precipitation levels for maintaining maize yields.

Moreover, Challinor [20] explored the effects of climate change on crop productivity globally, finding that yield responses vary significantly with cropping intensity and regional climatic conditions. This supports our conclusions regarding the importance of region-specific analysis and adaptation strategies. Bezner Kerr [12] also highlighted the complex interactions between climate variables and agricultural practices, emphasizing the need for integrated approaches to mitigate climate change impacts on food production. The authors [10] demonstrated the importance of continuous technological and management adaptations to cope with changing climate conditions. Our findings on the adverse effect of technological changes likely due to inadequate adaptation align with this study, underscoring the necessity for ongoing innovation in agricultural practices.

Several Slovak farms have successfully implemented innovative practices that could serve as models for others. For example, a farm in the Nitra region has adopted precision agriculture techniques that optimize water usage based on real-time soil moisture data, significantly improving water efficiency and crop yields [12]. These case studies high-

light the potential for tailored approaches to enhance the resilience and productivity of Slovak agriculture.

Examples of successful adaptations in Slovakia, such as precision agriculture techniques, demonstrate the potential for improving yields and water efficiency. These innovations can serve as models for other regions and countries [25].

Current agricultural policies in Slovakia do not adequately address regional climatic variations and their impacts on agriculture. There is a need to adapt policies to support region-specific strategies and technologies capable of responding to changing climatic conditions [22].

Furthermore, several recent studies have successfully utilized the Just and Pope model for their analyses. The authors [33] applied the model to assess the impact of climate change on dryland wheat yield in Iran, finding significant effects of temperature and precipitation on yield variability. The study from 2020 [50] conducted a systematic review of crop yields under climate change in China, utilizing the Just and Pope model to capture the impacts of climatic factors on yield trends. In 2020 [51], the authors analyzed the distributional and temporal heterogeneity in the climate change effects on US agriculture, emphasizing the model's robustness in assessing yield variability due to climatic factors. Similarly, the study from 2021 [21] used the Just and Pope model to study the heterogeneous response of rice yield to climate factors in Punjab, Pakistan, demonstrating the model's effectiveness in assessing climate impacts on crop variability. In their study from 2004, the authors [5] employed the Just and Pope model to analyze climate impacts on grain yields in China, highlighting the model's ability to capture yield variability due to climatic factors. The authors [52] also used this model to study the impact of climate on crop production in the United States, providing insights into the role of climatic variability in agricultural yields.

Overall, this study's results confirm that climatic variables, including temperature and precipitation, significantly impact maize production in Slovakia. Nonlinear relationships between these variables and yields highlight the need to optimize climatic conditions for maximum productivity. The results emphasize the need for regionally specific, sustainable adaptation strategies to improve agricultural resilience to climate change. These findings serve as a basis for developing policies and practical measures that prioritize sustainability to maintain and increase agricultural productivity in changing climatic conditions.

Slovakia experiences specific climatic challenges that differ significantly from those in other countries. For instance, regions such as Trnava and Žilina face stark differences in precipitation, which impacts crop yields and necessitates region-specific agricultural practices [16].

This article's main contribution is its comprehensive and regionally specific approach to analyzing the impact of climate change on maize production in Slovakia, with an emphasis on sustainability. In contrast to many existing studies that focus on global trends or broad geographical areas, this article provides a detailed analysis at the national level with an emphasis on regional differences and sustainable practices. This study is the first to validate these findings for the territory of the Slovak Republic.

Additionally, this study integrates advanced econometric methods to account for non-linear relationships and interaction effects, offering a more nuanced understanding of climatic impacts on agriculture. By leveraging the Just and Pope model, it provides robust statistical evidence that can inform adaptive strategies and policy interventions tailored to regional specifics. Furthermore, the findings contribute to the global discourse on climate change by adding valuable data from a previously underrepresented region in climate-agriculture studies.

Another significant contribution is the methodological advancement demonstrated by this study. By applying the Just and Pope model to a specific regional context, it provides a methodological framework that can be adapted for similar analyses in other regions. This methodological innovation is particularly important for accurately capturing the complex interactions between climatic variables and agricultural productivity. The policy implications of this study are substantial. By identifying the specific climatic

variables that significantly impact maize yields, policymakers can develop targeted interventions to mitigate these effects. For instance, adaptive measures such as altering planting dates or improving irrigation practices can be implemented based on the study's insights. This can lead to more effective resource allocation and better preparedness for adverse climatic conditions.

Research shows that agricultural strategies effective in one region may not be directly transferable to another due to differing environmental and socio-economic conditions. For instance, while certain irrigation techniques have proven successful in the arid regions of Australia, they may not be feasible in Slovakia due to its higher average annual precipitation and different soil composition [1]. Similarly, the adoption of genetically modified crops in the United States has led to increased yields, but such practices face significant regulatory and public resistance in Slovakia [2].

International studies show that climate change has varying impacts on agriculture across different parts of the world. For instance, while higher temperatures may increase yields in Northern Europe, they cause yield declines in Southern Europe and the Mediterranean [17].

The findings of this study highlight the necessity for region-specific sustainable adaptation strategies to improve agricultural resilience to climate change. The adoption of such strategies, as evidenced by successful case studies in Slovakia, underscores the potential for tailored approaches to significantly enhance Slovak agricultural productivity and sustainability [1,2,12].

Based on this study, further studies can be formulated and addressed. The obtained insights and identified relationships between climate variables and maize production provide a robust foundation for additional research. These results can be used to analyze the impact of climate change on various agricultural crops and develop effective, sustainable adaptation strategies. They can also serve as a model for similar studies in other regions, thereby contributing to a better understanding of the global impacts of climate change on agriculture and promoting sustainability in agricultural practices.

## 5. Conclusions

The conclusion of this study shows that climate variables, such as temperature and precipitation, significantly affect maize production in Slovakia. The analysis results confirm that extreme temperatures and precipitation variability can negatively impact maize yields. The study also identified nonlinear relationships between temperature, precipitation, and yields, emphasizing the need to optimize climatic conditions to achieve maximum productivity. The findings of this study highlight the necessity for region-specific, sustainable adaptation strategies to improve agricultural resilience to climate change. They can serve as a basis for developing policies and practical measures to maintain and increase agricultural productivity in a changing climate sustainably. Moreover, this study highlights that Slovakia's unique climatic and environmental conditions necessitate a development path distinct from the rest of the world. Unlike other regions where uniform strategies might be effective, Slovakia faces specific challenges such as significant regional variations in temperature and precipitation. These factors underscore the need for region-specific, sustainable adaptation strategies.

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