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The Impact of Agricultural Inputs and Climate Variability on Maize (*Zea Mays* L.) Production in Romania, 1990-2024

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ABSTRACT

Maize is one of the strategic cereal crops in Romania, with multiple uses in human consumption, industrial processing, and animal feed. In favourable agricultural years, national maize production can account for up to approximately 30% of the total production of the European Union. Despite its major economic importance, maize production is constrained by limited investment in modern agricultural technologies, high input costs, climate change, and insufficient irrigation infrastructure.

The study analyses the impact of agricultural inputs and climate variability on maize (*Zea mays L.*) production in Romania for the period 1990-2024, using a log-linear econometric model applied to time series data derived from national statistics and global climate and meteorological databases. The analysis integrates technological variables (nitrogen fertilization and herbicide use), climatic factors (precipitation and temperature during the growing season), as well as a structural variable (the share of maize cultivated area at the national level). The analysis uses official statistics from the Romanian National Institute of Statistics and climatic data from the NASA POWER database, harmonized to ensure temporal comparability.

The results show that nitrogen fertilization has a positive and statistically significant effect on production, confirming its essential role in supporting agricultural yields. In contrast, herbicide use shows a significant negative coefficient, suggesting that it reflects unfavourable agronomic conditions rather than a direct effect on production. Temperature has a negative and significant impact, indicating the high sensitivity of maize to thermal stress beyond certain thresholds, while precipitation has a positive but statistically weak effect.

Overall, the results highlight the need to optimize nitrogen fertilization and to adapt agricultural technologies to changing climatic conditions, while also emphasizing the limitations associated with the use of aggregated national data in the analysis of agroclimatic relationships.

Keywords: maize, nitrogen, herbicides, climate variability, temperature, precipitation, econometric model, Romania.

INTRODUCTION

Maize is one of the important agricultural crops in Romania, being present in the local area since the 17th-18th centuries. Originating from America, its introduction into the region is explained by two possible routes: the Balkan route, associated with Ottoman influence in Wallachia and Moldova, and the Central European route, through Habsburg Transylvania. The crop spread rapidly, becoming a staple food in rural areas, especially during periods of famine and agrarian crisis (Grigoriev, 2025). At the global level, maize plays an essential role in food, livestock production, and industry. Romania holds an important position on the European market due to favourable natural conditions; however, competitiveness depends on the technologies used, productivity, and market structure. Organic farming and integration into the international market represent relevant directions for development (Dragomir et al., 2022). Although yields are moderate, the large cultivated areas place Romania among the main European and global producers. In recent years, there has been a shift toward high-performance hybrids adapted to local conditions and modern technological requirements [Stoica (Dincă) et al., 2018, 2019]. Maize production plays an important role in Europe, with growth over the last decade driven by technological progress and

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favorable pedoclimatic conditions (Ghiorghe and Turek-Rahoveanu, 2022). Although Romania is a relevant actor within the European Union, yields per hectare remain below the EU average. The evolution of national production depends mainly on productivity rather than cultivated area, highlighting the importance of modern technologies, fertilization, and crop management (Popescu, 2017). Maize is important for livestock, the food industry, and human nutrition, providing energy and bioactive compounds with beneficial health effects, which places it among functional foods (Pech-Almeida et al., 2021).

Maize (*Zea mays* L.) is adaptable to various climatic conditions, from temperate to tropical zones, but optimal development requires average daily temperatures above 15°C and the crop is sensitive to frost. The growing period generally ranges between 80 and 140 days, depending on the variety and thermal conditions. Productivity is influenced by hybrid, water availability, and plant density, with the Food and Agriculture Organization (FAO) recommending alignment of crop requirements with local pedoclimatic conditions (FAO, 2023a). Maize fertilization must be correlated with the crop's high nutrient requirements and soil properties, especially pH and nutrient retention capacity. Nitrogen (20-33 kg/t) supports vegetative growth and yield formation, phosphorus promotes root development and maturity, and potassium contributes to water balance and stress resistance. On light soils with high leaching, split fertilizer application is recommended. The optimal pH range (6.0-7.2) ensures nutrient availability, while extreme values may cause deficiencies or nutrient lock-up, requiring adaptation to local conditions (ICL Growing Solutions, 2023). Potassium fertilization on calcareous chernozem soils, combined with optimal plant density, increases yield and mineral content. However, K-Ca-Mg interactions may affect nutrient uptake, requiring integrated management of fertilization and density to optimize maize production (Csathó et al., 2025). Differentiated nitrogen and mineral fertilizer application significantly influences production in southern Romania. Optimal doses and adapted fertilizers can increase yield, but efficiency depends on climatic conditions, and excess nitrogen in dry years may become limiting, highlighting the need for flexible fertilization management (Velicu and Ion, 2024). Adaptive nitrogen management, including slow-release fertilizers and split application according to growth stages, improves yield and nutrient use efficiency without affecting phenological stages (Haraga et al., 2025). Nitrogen fertilization also influences maize quality, including protein and starch content, with optimal doses improving both yield and nutritional value, while improper use may have limited or negative effects (Omar et al., 2022). Fertilizer costs and quantities depend on production orientation, farm type, market conditions, and agricultural policies. Specialization in crop production affects fertilizer efficiency and economic risks, requiring adapted management strategies (Kubala, 2024). Mineral fertilizer consumption directly influences agricultural productivity, being linked to economic development and intensification, but also generating environmental pressure (Piwowar, 2022). Climate variability significantly affects global agricultural production, with changes in temperature and precipitation reducing yields of major crops, including maize (Ray et al., 2015; Lobell et al., 2011). Nutrient management, especially nitrogen and water, is essential for reducing yield gaps and increasing productivity, contributing to sustainable agricultural systems (Mueller et al., 2012; Zhang et al., 2015). Adapting soil-plant management systems by aligning fertilization with climatic conditions enhances nutrient efficiency and global food security (Chen et al., 2011). Climate change may affect nitrogen use efficiency, with significant effects on maize productivity (Cammarano et al., 2020). Long-term water deficit is a major limiting factor for maize production, negatively affecting yield and nutrient efficiency (Daryanto et al., 2016; Nistor et al., 2020). Increasing extreme climate events, especially drought, generate significant risks for agriculture, including in the Romanian Plain (Sima et al., 2015; Spinoni et al., 2017). Efficient fertilizer use is essential for maintaining productivity and reducing environmental impact (Tilman et al., 2002). Maize productivity depends on fertilizer type and application method, with combined organic and mineral fertilization having positive effects on yield and quality, including under climate change conditions (Dușa et al., 2025). Cereal production in Romania is influenced by climate change and market dynamics, with yields depending on climate variability and input costs, requiring technological adaptation and resource optimization (Popescu et al., 2022). Drought is a major risk factor for maize in Romania, affecting yields and production stability, with southern areas more vulnerable. Its economic impact requires adaptation measures such as irrigation, resistant hybrids, and efficient resource management (Barna and Manescu, 2025). Modern technologies support adaptation to climate change and improve maize production, while minimum tillage systems can increase yields under favourable conditions. The use of adapted hybrids enhances performance and resilience (Botoș et al., 2025). Climate variability, especially drought and high temperatures, reduces hybrid performance, while new hybrids show better tolerance to abiotic stress (Călugăr et al., 2024). Under climate change conditions, successive cropping systems using maize hybrids improve land use efficiency and production (Olteanu et al., 2025). Climate change also affects water consumption, increasing irrigation demand and requiring improved water management (Nițu et al., 2023).

Therefore, this study aims to quantify the effects of nitrogen fertilization, herbicide use, temperature, precipitation, and cultivated area on maize production in Romania during 1990-2024 using a log-linear econometric model.

MATERIAL AND METHODS

The literature review was based on validated scientific sources (open access articles, institutional databases, and official statistics), with a focus on maize (*Zea mays* L.). Publications were selected from recognized scientific platforms (MDPI, Copernicus, Frontiers, PLOS, DOAJ, CORE) and from documents issued by organizations such as the Food and Agriculture Organization, the European Environment Agency, Eurostat, and the Intergovernmental Panel on Climate Change.

The analysis addressed the influence of climatic factors, the role of fertilization, and the interaction between pedoclimatic conditions and crop performance. The selected sources enabled the development of a robust and reproducible methodological framework, aligned with the study objectives.

Climatic data were obtained from NASA POWER, which provides validated time series of meteorological parameters. For the period 1990-2024, monthly precipitation data were collected at the national level for Romania, and national averages were calculated using weighted aggregation. The analysis focused particularly on the June-August interval, corresponding to the critical growth stages of maize, characterized by high water demand. For this period, total precipitation values were determined and subsequently used in the statistical analysis (Liu et al., 2013; FAO EcoCrop, 2023b).

Agricultural data were obtained from official sources, using time series from INS Tempo Online (1997-2024), validated through reports of the Ministry of Agriculture and Rural Development. The analyzed variables included cultivated area, total production, and yield, and the datasets were verified and completed using conservative interpolation methods. Preliminary relationships between precipitation during the growing season and maize crop performance were investigated using the Pearson correlation coefficient (r), scatter plot representations, and simple linear regression models (Trnka et al., 2014; Ray et al., 2015). Subsequently, the combined influence of agricultural inputs and climatic variables on yield was analysed using a multivariate log-linear econometric model.

The relationship between maize yield and its determinants was analysed using a log-linear regression model, which allows the interpretation of coefficients as elasticities (formula 1).

$$\ln(Y)=\alpha+\beta_1\ln(N_{ha})+\beta_2\ln(Erb_{ha})+\beta_3 Rain_{maize}+\beta_4 Temp_{maize}+\beta_5 Share_{maize}+\varepsilon \quad (1)$$

Where:

Y = maize yield (kg/ha)

N_{ha} = nitrogen input per hectare (kg N/ha)

Erb_{ha} = herbicide application, expressed as kilograms of active substance per hectare (kg a.i./ha)

$Rain_{maize}$ = precipitation during April-September (mm). Total precipitation during the relevant phenological interval (typically June-August, extended to April-September), expressed in mm

$Temp_{maize}$ = average temperature during April-September (°C)

$Share_{maize}$ = share of maize cultivated area (%)

ε = error term.

The selection of explanatory variables was based on the literature and agronomic relevance for maize cultivation. Nitrogen fertilization (N_{ha}) was included as the main technological input due to its essential role in growth and yield formation, while herbicide use (Erb_{ha}) reflected weed management and technological intensification.

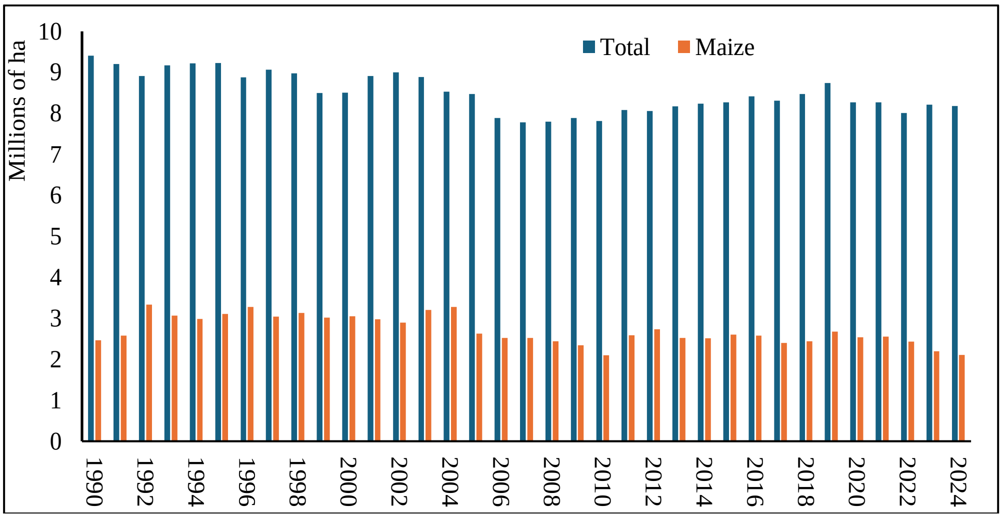
Climatic variables were represented by total precipitation (Rainmaize) and average temperature (Tempmaize) during April-September, key determinants of yield. The share of cultivated area (Sharemaize) was included as a structural control variable. The model is grounded in agronomic theory and empirical studies on the role of fertilization and climatic factors (Tilman et al., 2002; Ray et al., 2015; Cammarano et al., 2020).

Artificial intelligence tools were used exclusively for linguistic proofreading and ensuring textual coherence. Data processing, statistical analysis, and interpretation of results were carried out entirely by the authors, without affecting the originality, methodology, or scientific content of the study.

RESULTS AND DISCUSSION

Evolution of maize cultivated area in Romania

Figure 1 presents the evolution of cultivated area (million ha) for cereals and maize in Romania (1990-2024). The data indicate a relatively stable trend of the total cultivated area, ranging between approximately 7.8 and 9.3 million hectares, with limited variations.



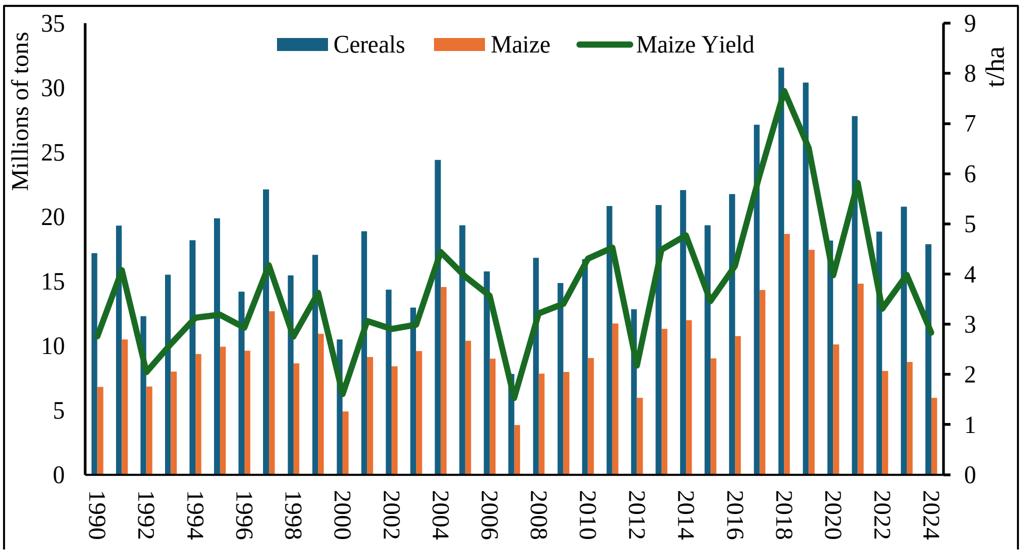
Source: Authors' processing based on data from the National Institute of Statistics (INS), Tempo Online database (2026).

Figure 1. Evolution of the cultivated area of cereals and maize in Romania (1990-2024)

After the high levels recorded in the 1990s, associated with an extensive system, the cultivated area slightly declined during 2000-2009, followed by stabilization. The maize cultivated area ranged between 2.1 and 3.3 million ha, with higher values in the 1990s and a decrease during 2007-2012, followed by stabilization. Maize maintained a constant share of 25%-30% of the total cereal area, confirming its strategic role. The dynamics reflect farmers' adaptation to climatic, economic conditions, and agricultural policies.

Total cereal production and maize production in Romania (1990-2024)

Figure 2 presents the cereal and maize production, and maize yield in Romania (1990-2024). The evolution of cereal and maize production in Romania (1990-2024) shows high variability, driven by climatic factors and structural changes.



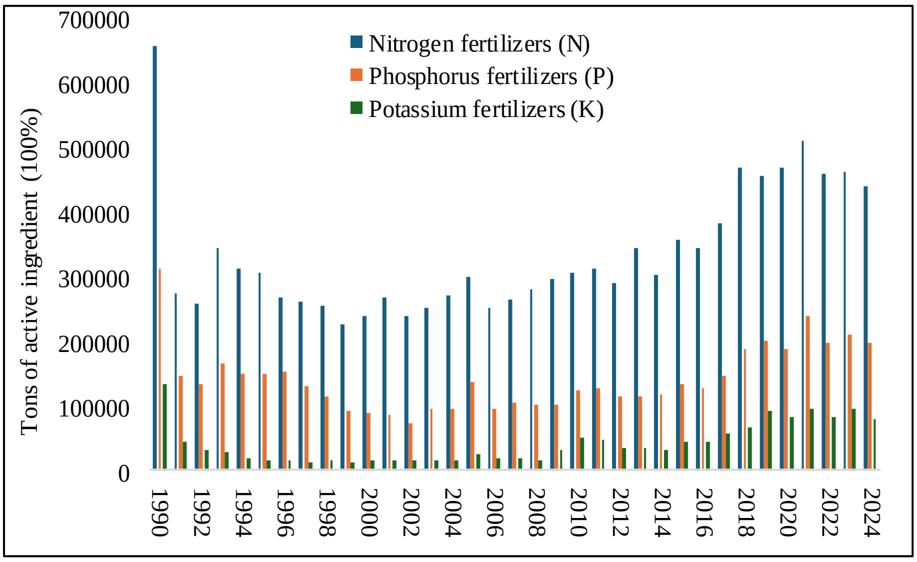
Source: Authors' processing based on data from the National Institute of Statistics (INS), Tempo Online database (2026).

Figure 2. Trends in total cereal production, maize production, and average maize yield in Romania, 1990-2024

After low levels in the 1990s, production increased after 2000, reaching record levels in 2017-2019, mainly due to technological modernization and increased input use. Compared with total cereal production, maize exhibited greater year-to-year variability, reflecting its higher sensitivity to drought and heat stress during the flowering and grain-filling stages. The increase after 2010 is associated with high-performance hybrids and improved agricultural practices. Yield confirms the intensification trend, and production variability depends mainly on productivity rather than cultivated area, highlighting the role of technology and climatic factors.

Total consumption of mineral fertilizers by type (N, P, K) in Romania (1990-2024)

Figure 3 presents the dynamics of nitrogen, phosphorus, and potassium fertilizer consumption (tons of active substance) in Romania during 1990-2024. The evolution highlights significant changes in the structure and intensity of agricultural input use. A relevant aspect is the high level of nitrogen fertilizer consumption in 1990, associated with an intensive agricultural model.



Source: Authors' processing based on data from the National Institute of Statistics (INS), Tempo Online database (2026).

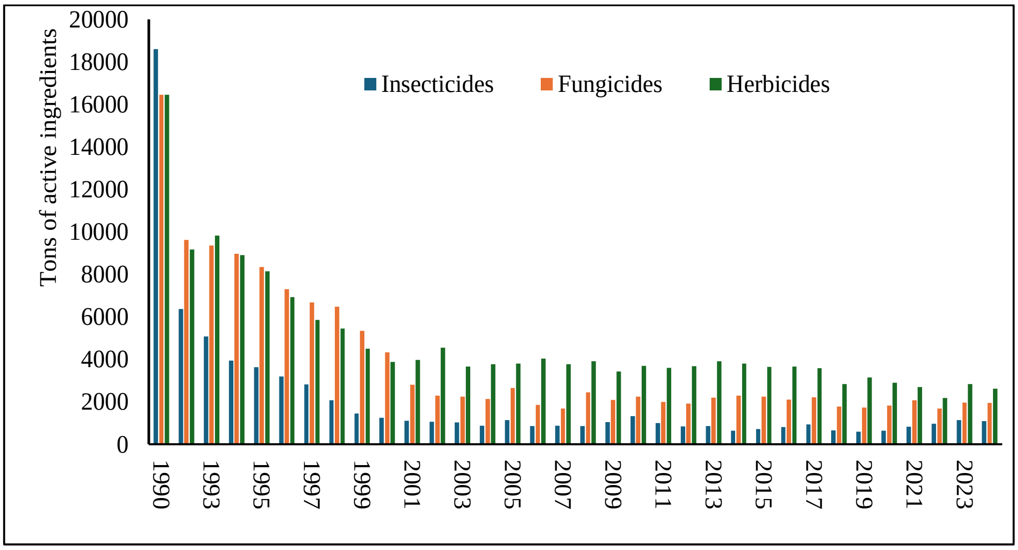
Figure 3. Trends in nitrogen (N), phosphorus (P), and potassium (K) fertilizer consumption in Romania, 1990-2024.

Subsequently, consumption declined sharply due to sector restructuring and limited access to inputs, followed by a recovery after 2000, intensified after EU accession. Nitrogen remains predominant, but at more rational levels, while the low use of P and K suggests a possible nutrient imbalance. For maize cultivation, these trends are relevant due to high nutrient requirements. Increased fertilization supported yields, but nitrogen efficiency depends on climatic conditions, being reduced in dry years. The results highlight the need to optimize fertilization and adapt to climatic conditions to ensure sustainability.

Plant Protection Inputs in Romanian Agriculture (1990-2024)

Figure 4 illustrates the evolution of plant protection product consumption in Romania, highlighting the dynamics of insecticides, fungicides, and herbicides during 1990-2024, expressed in tons of active substance. INS data indicate a sharp decline in consumption after 1990 until 2000, followed by a stabilization period and a slight recent increase. The high levels in the 1990s reflect the intensity of agriculture during the communist period. The subsequent decrease was driven by sector restructuring, farm fragmentation, and limited access to inputs during the transition period. In the long term, herbicide use is higher compared to insecticides and fungicides, indicating the priority given to weed control, particularly relevant for maize cultivation. The reduced use of insecticides may reflect more efficient control strategies or the use of more resistant hybrids, also influenced by economic constraints.

At the same time, the relative increase in fungicide use suggests greater attention to disease control in the context of climate variability. In maize cultivation, the dynamics of these inputs are correlated with productivity, as weed control plays a key role in yield stability, while pesticide use becomes increasingly important under rising biotic pressure.



Source: Authors' processing based on data from the National Institute of Statistics (INS), Tempo Online database (2026).

Figure 4. Evolution of insecticides, fungicides and herbicides consumption in Romania (1990-2024), expressed in tons of active ingredient

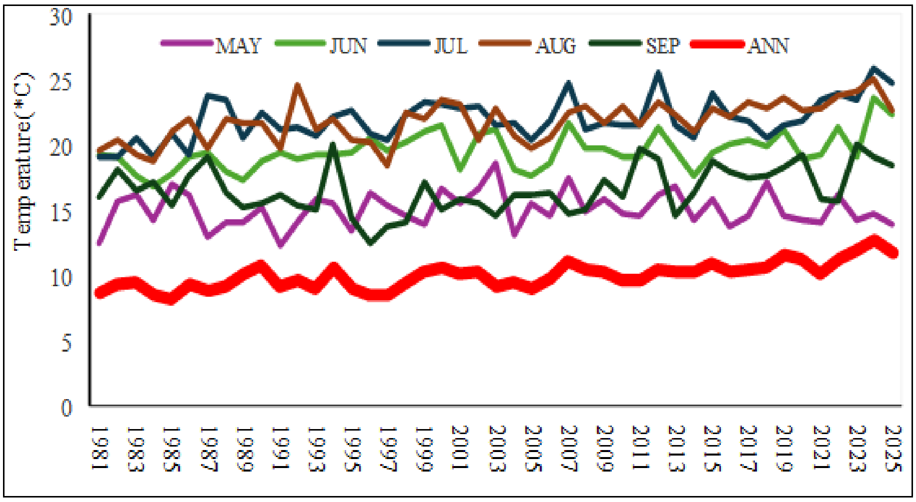
A more rational and adaptive use of plant protection products can be observed, in line with the requirements of modern and sustainable agriculture. The cultivation of genetically modified maize (MON 810 hybrid) reached a peak in 2007-2008, when Romania ranked among the top countries in Europe, followed by a significant decline, partly due to the reduced pressure of the European corn borer [Munteanu (Pila) and Stanciu, 2019; Stanciu and Sârbu, 2019].

The reduction in cultivated areas is associated with legislative constraints, variability in performance under local conditions, changes in farmers' preferences, environmental concerns, and consumer reluctance. After 2015, the cultivation of genetically modified maize was practically abandoned in Romania, with only conventional hybrids adapted to local conditions being used (European Commission, 2023).

Climatic factors

Average temperatures during the maize growing season

Figure 5 illustrates the evolution of average temperatures during the maize growing season (May-September) and the annual average, highlighting the warming trend in Romania. The data show a constant increase in temperatures, with maximum values in July-August, corresponding to the critical growth stages of the crop. The intensification after 2000 reflects climate warming, with direct effects on maize production. Moderate temperatures promote vegetative growth and grain formation, whereas temperatures exceeding the physiological optimum during flowering and grain filling can reduce pollen viability, kernel set, and final grain yield, particularly when accompanied by limited soil moisture.



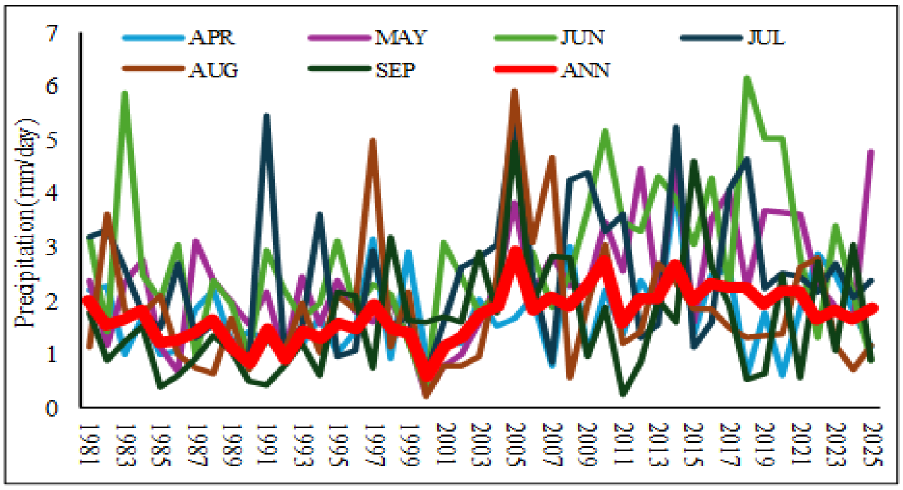
Source: Author's processing based on NASA POWER data (NASA, 2025).

Figure 5. Evolution of monthly and annual average temperatures during the maize growing season in Romania (1980-2025)

The increasing interannual variability also suggests greater climatic uncertainty, which may contribute to larger fluctuations in maize yields despite ongoing technological improvements.

Monthly precipitation averages

The precipitation analysis highlights the evolution of monthly and annual values during the critical period June-August (Figure 6). The data show high interannual variability, without a clear trend, characteristic of a temperate-continental climate, with dry years (2000, 2007, 2011, 2020, 2024) and wet years (2005, 2010, 2014, 2017). Years with below-average precipitation during June-August generally coincided with lower maize production because water deficits during flowering and grain filling substantially reduce kernel development and grain yield. Conversely, years with adequate rainfall during the reproductive period were generally associated with higher yields, highlighting the importance of water availability during the crop's most sensitive growth stages. Overall, the results in Figure 6 show that precipitation distribution, especially in June-August, plays a decisive role in maize production in Romania. The high variability of the precipitation regime largely explains annual yield fluctuations. The systematization of data on maize productivity and input variables (fertilizers, plant protection, temperature, and precipitation) is presented in Equation 1.



Source: Author's processing based on NASA POWER data (NASA, 2025).

Figure 6. Evolution of monthly and annual mean corrected precipitation during the critical maize growing period in Romania (1980–2025), expressed in mm/day (NASA POWER, MERRA-2).

Table 1 summarizes the variables included in the econometric analysis. The dataset combines official agricultural statistics from the National Institute of Statistics with climatic indicators derived from the NASA POWER database. Agricultural inputs were normalized on a per-hectare basis, while climatic variables were aggregated over the April-September growing season. (Table 1).

Table 1. Dataset final

Year	Y	N_{ha}	Erb_{ha}	Rain	Temp	Share
1990	2756	69.8	1.97	182	17.31	0.26
1991	4072	29.9	1.15	320	16.83	0.28
1992	2046	29.0	1.10	210	17.73	0.37
1993	2605	37.7	0.98	275	16.96	0.33
1994	3131	34.0	0.90	240	18.33	0.32
1995	3184	33.1	0.86	310	16.90	0.34
1996	2926	30.1	0.82	285	16.70	0.37
1997	4171	29.0	0.78	360	15.90	0.34
1998	2756	28.3	0.70	300	17.77	0.35
1999	3627	26.5	0.65	330	17.38	0.35
2000	1603	28.1	0.60	95	18.62	0.36
2001	3066	30.2	0.58	240	17.15	0.33
2002	2902	27.0	0.57	260	17.70	0.32
2003	2993	28.4	0.55	310	17.98	0.36
2004	4441	31.7	0.60	350	16.99	0.38
2005	3952	35.3	0.75	480	16.87	0.31
2006	3565	30.0	0.70	340	17.65	0.32
2007	1526	32.2	0.72	260	18.56	0.32
2008	3215	35.9	0.80	320	17.38	0.32
2009	3409	37.6	0.85	360	17.78	0.31
2010	4309	38.8	1.10	480	17.62	0.30
2011	4525	40.1	1.20	300	17.84	0.27
2012	2180	36.0	1.05	280	19.45	0.32
2013	4488	42.7	1.00	360	17.93	0.34
2014	4770	37.2	1.05	500	16.60	0.31
2015	3462	43.4	1.10	330	18.21	0.30
2016	4159	41.7	1.15	370	18.13	0.31
2017	5959	45.4	1.20	390	17.72	0.31
2018	7644	55.8	1.25	410	18.65	0.29
2019	6502	53.9	1.20	330	18.76	0.29
2020	3977	56.7	1.15	360	17.79	0.31
2021	5802	61.8	1.25	330	17.44	0.31
2022	3298	55.5	1.20	310	18.83	0.31
2023	3982	56.1	1.30	300	18.89	0.30
2024	2829	53.9	1.35	290	20.94	0.26

Source: Author's own processing data.

The share of cultivated area was included as a structural control variable. The annual dataset, constructed in accordance with agronomic theory, allows the assessment of the influence of inputs and climatic factors on yield. Precipitation was calculated from NASA POWER daily data, converted into monthly values and then aggregated seasonally.

A total of 35 observations corresponding to the period 1990-2024 were analysed.

The model performance indicators are:

$$R^2 = 0.572$$

adjusted R^2 = 0.496, and Prob. F = 0.000144.

$\ln(Y) = 2.245 + 0.551 \ln(N_{ha}) - 0.346 \ln(Erb_{ha}) + 0.0005\ Rain_{maize} - 0.184\ Temp_{maize} - 0.0068\ Share_{maize}$,

where productivity Y is expressed in tons/ha. The estimated model highlights the differentiated role of technological and climatic factors in determining maize production in Romania, largely confirming theoretical assumptions while also revealing specific features of aggregated data.

Nitrogen fertilization (N_{ha}) – positive and significant effect (p = 0.042)

The positive coefficient (+0.551) of ln(Nha) indicates a direct and significant impact of nitrogen fertilization on production, with an elasticity (~0.55) suggesting that a 1% increase in nitrogen leads to an approximately 0.55% increase in yield. This result is agronomically justified, as nitrogen is the main limiting nutrient (Tilman et al., 2002; Mueller et al., 2012), and its increased use after 2010 partly explains production growth. The sub-unitary elasticity indicates diminishing marginal returns and lower efficiency at higher application rates, influenced by climatic conditions (Ray et al., 2015; Zhang et al., 2015).

Herbicide use (Erb_{ha}) – negative and significant effect (p = 0.037)

The negative coefficient (−0.346) of ln (Erb_{ha}) does not indicate a direct negative effect of herbicides but rather reflects their indirect role. Herbicides support yield maintenance by reducing weed competition, without directly increasing productivity. In aggregated data, higher herbicide use is often associated with unfavourable agronomic conditions, explaining the negative sign. Thus, the relationship reflects the association "unfavourable conditions - higher input use" rather than a causal negative effect, acting as an indicator of technological intensity and biotic pressure.

Precipitation ($Rain_{maize}$) – positive but weak effect (p = 0.309)

The positive coefficient of $Rain_{maize}$ (+0.0005) confirms the favourable role of precipitation, but the lack of statistical significance indicates difficulty in isolating its effect. This result is influenced using a seasonal total, which does not capture distribution during critical stages (Lobell et al., 2011), as well as by interactions with temperature and fertilization (Tilman et al., 2002; Ray et al., 2015). Aggregated data may also mask regional variability (Lobell and Burke, 2010). Small coefficient reflects the measurement unit, with an increase of 100 mm being associated with approximately a 5% increase in yield. The results suggest the need for more detailed climatic variables or interaction terms.

Temperature ($Temp_{maize}$) – negative and significant effect (p = 0.010)

The negative and significant coefficient of temperature (−0.184) highlights the impact of heat stress on production, with increases above the optimal level associated with yield reductions. Temperatures exceeding 30°C may impair pollination and shorten the crop cycle. This result is consistent with the literature, which shows that high temperatures reduce biomass accumulation and grain formation, indicating increased maize vulnerability to climate warming (Herrero and Johnson, 1980; Lizaso et al., 2018; Waqas et al., 2021; Niu et al., 2024).

Share of cultivated area ($Share_{maize}$) – non-significant effect (p = 0.784)

The coefficient of $Share_{maize}$ is low and not statistically significant, indicating that crop structure does not directly influence yield and serves mainly as a control variable. The results show that production is primarily driven by nitrogen fertilization and climatic conditions, especially temperature, with input efficiency constrained by the natural environment. The model also highlights the limitations of aggregated data in capturing the effects of precipitation and crop protection practices.

CONCLUSIONS

The study analyses the determinants of maize production in Romania using a log-linear econometric model that integrates technological and climatic factors.

The results confirm the essential role of nitrogen fertilization, with a positive and significant effect, while the sub-unitary elasticity indicates diminishing marginal returns. Herbicide use shows a negative coefficient, reflecting indirect effects and unfavourable agronomic conditions. Climatic factors are decisive, with temperature having a significant negative impact, while precipitation has a positive but statistically insignificant effect. The share of cultivated area does not exert a statistically significant direct effect on production, being mainly driven by inputs and climatic conditions.

The findings highlight the need to optimize fertilization and the limitations of aggregated data, suggesting the use of more detailed climatic indicators. These findings support policies promoting optimized nitrogen management, precision agriculture, modernization of irrigation infrastructure, climate-resilient maize hybrids, and sustainable resource management to enhance the resilience and long-term productivity of the Romanian maize sector.

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