

GIS-BASED ASSESSMENT OF CLIMATE CHANGE CONSTRAINTS ON ROMANIAN AGRICULTURE AND FORAGE SYSTEMS

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Abstract. Climate change represents one of the major constraints affecting agricultural sustainability, forage productivity and grassland ecosystem stability worldwide. The present study aimed to assess the main climate-change constraints affecting Romanian agriculture and forage systems through an integrated approach combining scientific literature review and GIS-based spatial analysis. Climatic analyses were performed using ERA5-Land reanalysis datasets in NetCDF format for the April–October vegetation season. Mean temperature, precipitation amount and climatic anomalies were analyzed for the recent 2021–2025 interval relative to the 1991–2020 reference period. Spatial datasets related to drought indicators, land-cover categories and grassland distribution were integrated within a GIS environment in order to identify the most climate-vulnerable agricultural regions of Romania. The obtained results indicate a generalized increase in mean air temperatures during the vegetation season, with positive thermal anomalies exceeding +1.2 °C in several southern and south-eastern agricultural regions. At the same time, precipitation deficits and increasing aridization tendencies were identified especially in the Romanian Plain, Dobrogea, southern Oltenia and partially in western lowland areas. The combined effect of increasing temperatures and declining precipitation suggests an intensification of drought stress and growing vulnerability of forage systems and grassland ecosystems. The study also highlights the adaptive importance of drought-tolerant forage species such as *Medicago sativa*, *Festuca arundinacea* and *Onobrychis viciifolia* for maintaining forage productivity under increasing hydroclimatic stress. The originality of the study derives from the integration of climatic reanalysis datasets with GIS-based spatial assessment focused specifically on forage systems and agricultural vulnerability in Romania. The results may support climate-adaptation planning, sustainable grassland management and the selection of resilient forage species under future climate-change scenarios.

Keywords: climate change; GIS analysis; forage systems; grasslands; drought; aridization; Romania; agricultural vulnerability; adaptation strategies

INTRODUCTION

The importance of the agricultural sector derives from the fact that it represents one of the main pillars of the global economy, ensuring both food for humans and feed for animals. However, agriculture is also one of the sectors most dependent on edaphic, orographic and climatic resources, and at the same time one of the most exposed to the increasing impact of climate change. In recent decades, the concept of climate change has become widely used to describe long-term modifications in mean temperatures, precipitation patterns and other climatic parameters of the planet (SAMFIRA et al., 2026). At global level, numerous studies have shown that climate change is reflected in major alterations of temperature and precipitation regimes, with direct consequences for agricultural production, agricultural economic stability and the resilience of agroecosystems (DAHBI et al., 2025; SCHLENKER and ROBERTS, 2006; GODFRAY et al., 2010; FOLEY et al., 2011; TILMAN et al., 2011; AHMAD et al., 2026). When climatic stressors and their impacts threaten the stability of agroecosystems or of

natural ecosystems that are essential for sustainable development, additional pressure is placed on the food, energy and water resources required for human economic security and stability (HASAN et al., 2020; COHEN et al., 2021).

According to the IPCC Report (2023), it is unequivocal that human activities, through greenhouse gas emissions, have caused global warming. Among the main drivers are the unsustainable use of energy sources, consumption and production patterns associated with the modern lifestyle, and other anthropogenic activities. Recent climate changes are associated with increasing concentrations of greenhouse gases, such as carbon dioxide, methane and nitrous oxide, generated mainly by fossil fuel combustion and also by intensive agricultural practices (GWOREK et al., 2026). Nevertheless, agriculture also has an important mitigation potential, particularly through the increase of soil organic carbon content, a process known as carbon sequestration. Starting from these considerations, several agricultural practices have been promoted in recent years in order to enhance the sequestration of atmospheric carbon in soils, such as the implementation of no-till systems, the expansion of crops with deep root systems, including energy crops, the extension of forest and grassland ecosystems instead of traditional arable systems, and the prevention of soil erosion processes (CHENU et al., 2019; SZYMAŃSKI et al., 2021; LIU et al., 2024).

The impact of climate change on Romanian agriculture has brought into focus the need to adopt mechanisms aimed at reducing climatic vulnerability and improving the adaptive capacity of agricultural systems. Some of these mechanisms are similar to those promoted at European level and include the optimization of water management, together with the application of cropping technologies that improve soil water retention. In this context, agricultural adaptation is no longer limited to technological measures, but also requires spatially explicit assessments capable of identifying the regions, land-use categories and production systems most exposed to climatic stress.

It is also well known that the climate of Romania, and particularly that of the Banat region, has changed significantly in accordance with global climatic trends. A similar pattern has been observed in the form of increasing temperatures during the vegetation season, usually associated with a reduction in the amount of precipitation available for crop development (ȘMULEAC et al., 2020; JURCUȚ et al., 2025). These changes are particularly relevant for forage systems and grassland ecosystems, whose productivity and floristic composition are strongly influenced by the balance between temperature, precipitation and soil water availability. Therefore, the use of GIS-based spatial analysis can provide a useful methodological framework for identifying climate-change constraints affecting Romanian agriculture and forage systems.

MATERIAL AND METHODS

The present study is based on an integrated methodological approach combining a systematic literature review with a GIS-based spatial assessment of climate-change constraints affecting Romanian agriculture and forage systems. The literature review was used to identify the main effects of climate change on agricultural production, grassland ecosystems and forage species, while the GIS analysis was designed to highlight the spatial distribution of climatic constraints relevant for agricultural and forage systems.

Scientific sources were identified using academic databases and search platforms such as Google Scholar, ScienceDirect and other relevant scientific repositories. The selection of studies was based on keywords including: climate change, Romanian agriculture, forage species, grassland systems, drought, adaptation strategies, climatic constraints and GIS-based assessment. The

publications were screened and analyzed according to their scientific relevance, methodological quality and applicability to the Romanian agricultural context. The collected information was synthesized in order to identify the main climate-related pressures affecting agricultural systems, with particular attention to temperature increase, precipitation deficit, drought occurrence and changes in forage productivity.

The GIS component of the study was developed in order to provide a spatial interpretation of the climatic constraints discussed in the literature. Spatial processing and cartographic analyses were performed in ArcGIS Pro 3.5. The analysis focused on Romania, with particular attention to agricultural areas and grassland systems that are directly relevant for forage production. Spatial datasets referring to climatic variables, drought indicators and land-cover categories were integrated into a GIS environment. Climate-related variables considered for the analysis included mean temperature, precipitation amount and drought-related indicators, especially during the vegetation season, when agricultural crops and forage species are most sensitive to water deficit and thermal stress.

Land-cover information was used to identify agricultural areas and grassland surfaces potentially affected by climate-change constraints. The spatial analysis consisted of the integration and overlay of climatic and land-cover datasets, allowing the identification of areas where agricultural and forage systems may be more exposed to increasing temperatures, reduced precipitation and drought conditions. Where applicable, climatic data were aggregated at regional or administrative level in order to support the interpretation of spatial patterns and to relate them to agricultural vulnerability.

The methodological workflow included the following main steps: selection and review of relevant scientific literature; acquisition and preparation of spatial datasets; harmonization of coordinate systems and spatial resolution; extraction of climate-related indicators for the study area; overlay analysis between climatic constraints and agricultural or grassland land-cover categories; and interpretation of the results in relation to the adaptation potential of forage species. The results obtained through this approach were used to discuss the main spatial patterns of climate-change constraints in Romania and their implications for forage systems and agricultural adaptation strategies.

This combined approach allows the study to move beyond a general review of climate-change impacts and to provide a spatially explicit assessment of the areas and production systems that may be more vulnerable to climatic stress. Therefore, the GIS-based analysis represents a useful tool for supporting adaptation planning, particularly in relation to grassland management, forage species selection and the development of more resilient agricultural systems.

RESULTS AND DISCUSSIONS

3.1. Global climate-change context

Global warming driven by greenhouse gas emissions has caused an increase in global surface temperature of approximately 1.1 °C during the period 1850–2020. Moreover, greenhouse gas emissions have continuously increased during the last decades (Figure 1 and Figure 2).

Numerous scientific studies have demonstrated an increase in mean global temperature of approximately 1.1–1.3 °C compared with the pre-industrial period. The last decade has been considered the warmest period in recorded human history, leading to an intensification of extreme meteorological phenomena (IPCC, 2021; IPCC, 2023; WMO, 2023; NASA, 2024; MASSON-DELMOTTE, 2024; KAUFMAN and MASSON-DELMOTTE, 2024).

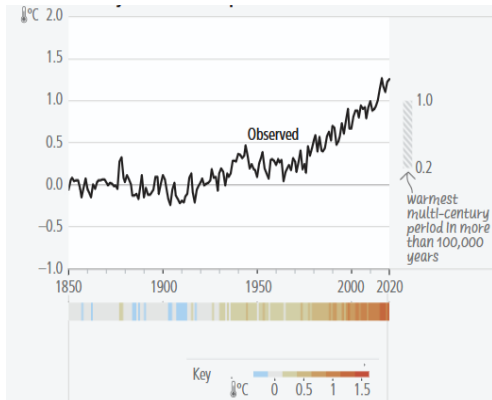


Figure 1. Global surface temperature increased in 2011-2020 compared with 1850-1900 (source: IPCC, 2023 accessed at: <https://www.ipcc.ch>)

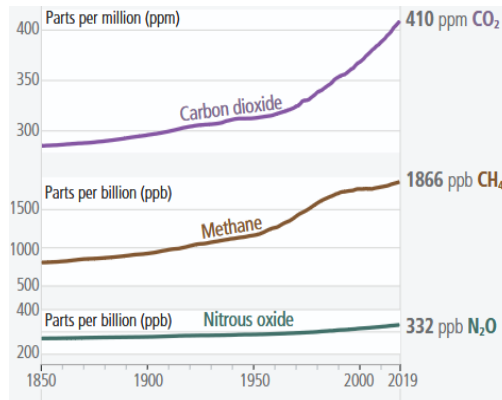


Figure 2. Rise in atmospheric greenhouse gas concentrations between 1850 and 2019 (source: IPCC, 2023 accessed at: <https://www.ipcc.ch>)

In general, climatic pressures degrade the natural climatic balance, while the era of industrial agriculture, characterized by large-scale monocultures, intensive pesticide use and deforestation, especially in wetland areas, contributes to biodiversity loss that could otherwise mitigate some of these negative effects.

3.2. Climate-change constraints on Romanian agriculture

Climate change primarily reduces water availability for agriculture, affecting both irrigation requirements and livestock farming activities. During 2024, several rivers in Romania dried up completely, while hundreds of localities introduced water consumption restrictions. These effects were particularly severe in the southern part of the Romanian Plain, Dobrogea and Moldova.

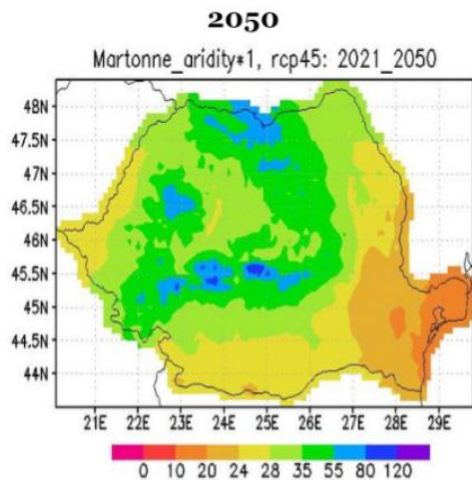


Figure 3. Projected changes in the aridity index in Romania for 2021–2050 (source: NIMH – National Institute of Meteorology and Hydrology, Romania)

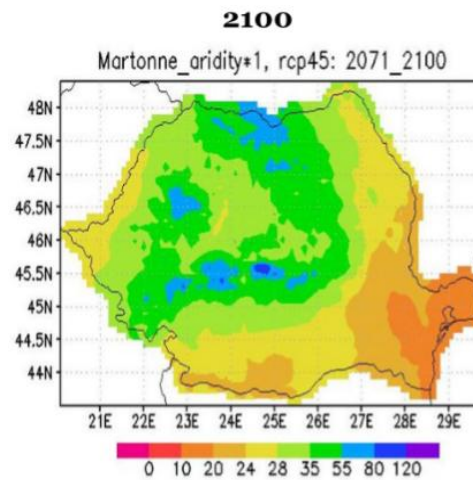


Figure 4. Projected changes in the aridity index in Romania for 2071–2100 (source: NIMH – National Institute of Meteorology and Hydrology, Romania)

One of the immediate consequences of climate change is desertification. In Romania, especially in the south-eastern regions of Muntenia and the south-western part of Oltenia, agriculture is increasingly affected by a growing number of extremely hot days and insufficient precipitation amounts, amplifying both atmospheric and soil water deficits. At the national level, increasing aridization can be observed, further enhancing the vulnerability of both natural ecosystems and agroecosystems.

Analysis of future climate projections for Romania indicates that the critical threshold established by the Paris Agreement, namely a temperature increase of 1.5 °C, will almost certainly be exceeded, while increases approaching 3 °C are projected for eastern and south-eastern regions by 2070 (Figure 3 and Figure 4).

3.3. GIS-based assessment of climatic constraints

The analysis was performed using ERA5-Land climatic reanalysis datasets in NetCDF format for the April–October vegetation season. The 1991–2020 interval was used as the climatic reference period, while 2021–2025 was considered representative of recent climatic conditions. Mean air temperature and total precipitation were extracted for Romania and processed within a GIS environment in order to calculate seasonal averages and climatic anomalies. The 2021–2025 interval does not represent a climatic normal, but was selected in order to characterize recent hydroclimatic tendencies and compare them with the long-term 1991–2020 reference period. Monthly ERA5-Land datasets were aggregated for the April–October vegetation season.

The resulting GIS analysis indicates a generalized increase in mean air temperature during the vegetation season across Romania. Mean temperatures during April–October reached values of approximately 20.9 °C in the southern regions of the country during 2021–2025, compared with maximum values of around 19.8 °C during the 1991–2020 reference period (Figure 5 and Figure 6). Positive temperature anomalies reached values exceeding +1.2 °C, particularly in southern and south-eastern Romania.

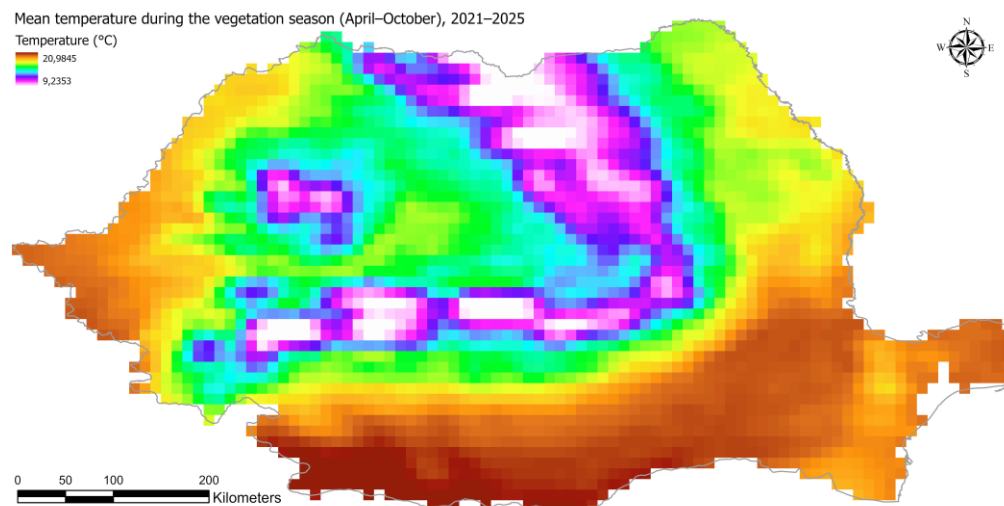


Figure 5. Mean air temperature during the vegetation season (April–October) in Romania, 1991–2020.

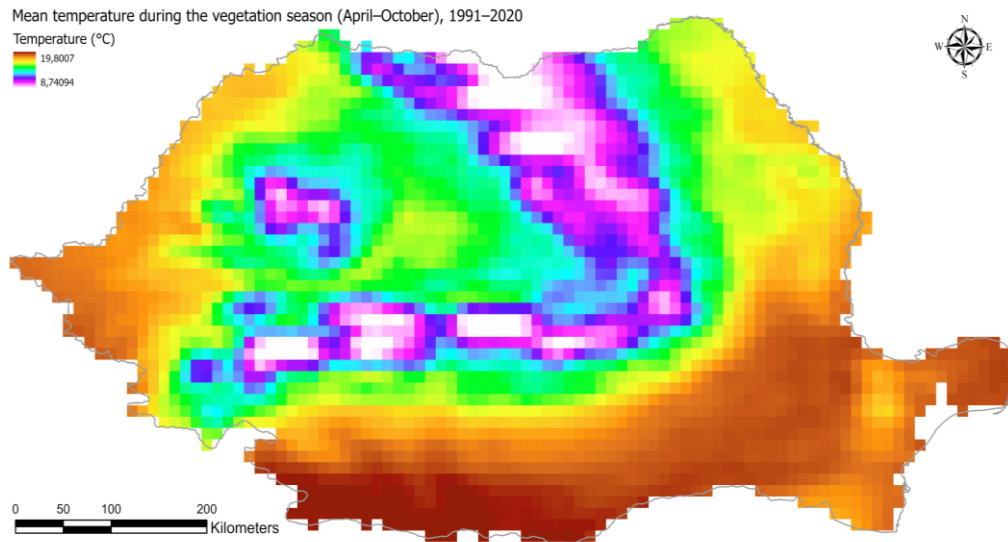


Figure 6. Mean air temperature during the vegetation season (April–October) in Romania, 2021–2025.

The strongest warming signal is concentrated in lowland agricultural regions, especially in the Romanian Plain, southern Oltenia, Muntenia and parts of Dobrogea, areas already characterized by elevated summer temperatures and recurrent water deficits. In contrast, mountainous and submontane regions of the Carpathians maintain lower mean temperatures due to altitudinal climatic control, although positive anomalies are still evident (Figure 7).

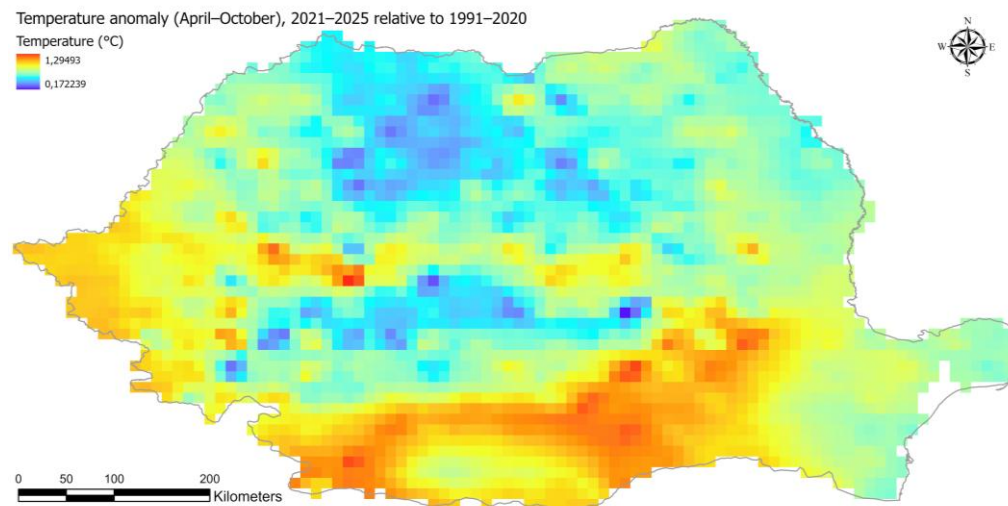


Figure 7. Temperature anomaly during the vegetation season (April–October) in Romania, 2021–2025 relative to 1991–2020.

The precipitation analysis highlights a reduction in total precipitation amounts during the vegetation season in several agricultural regions. Mean precipitation values decreased from approximately 1116 mm in the wettest mountain areas during 1991–2020 to around 858 mm during 2021–2025. Negative precipitation anomalies locally exceeded -300 mm, especially in south-western and southern Romania, suggesting increasing drought pressure and growing atmospheric water deficits (Figure 8 and Figure 9).

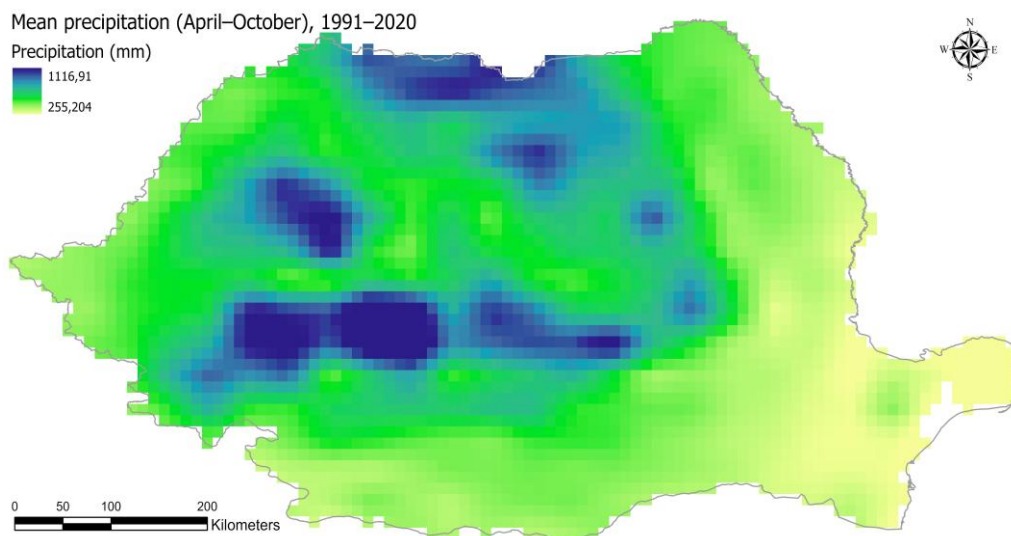


Figure 8. Mean precipitation during the vegetation season (April–October), 1991–2020

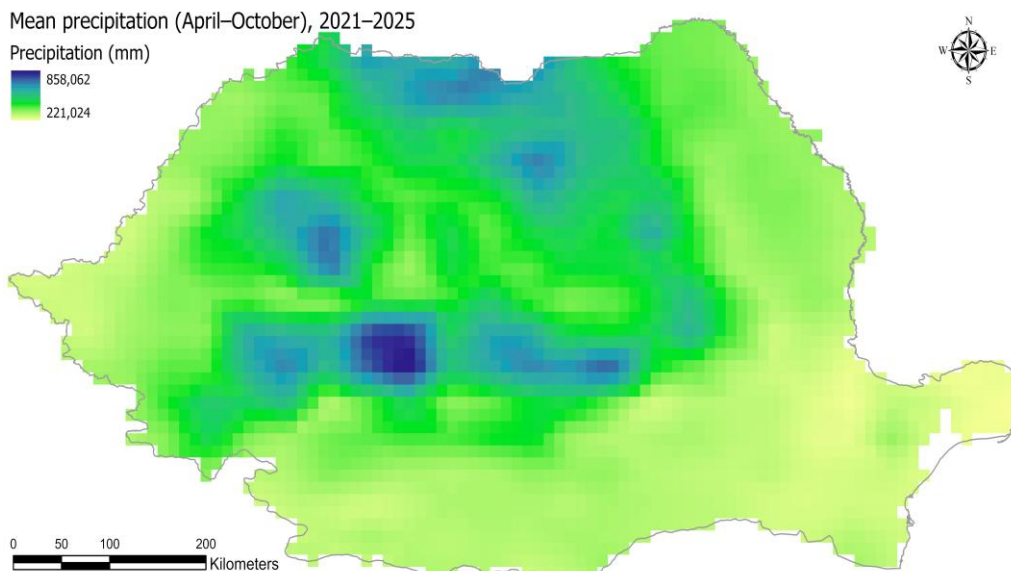


Figure 9. Mean precipitation during the vegetation season (April–October), 2021–2025

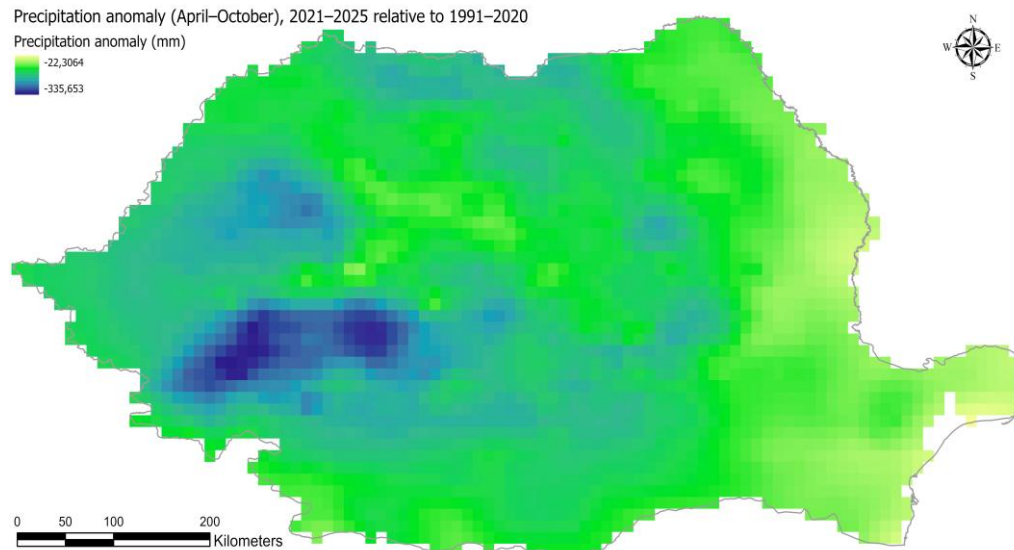


Figure 10. Precipitation anomaly (April–October), 2021–2025 relative to 1991–2020

The spatial distribution of both temperature increase and precipitation decline indicates that southern, south-eastern and partially western agricultural regions represent the most climate-vulnerable areas of Romania (Romanian Plain; Dobrogea; southern Oltenia; western Banat lowlands) (Figure 10). These regions are characterized by elevated evapotranspiration rates, prolonged summer droughts and increasing aridization tendencies.

The obtained results are consistent with projections provided by the National Meteorological Administration and the National Institute of Hydrology and Water Management, which indicate a future intensification of aridity processes, particularly in the Romanian Plain, Dobrogea and southern Oltenia. The GIS-derived spatial patterns therefore confirm the progressive expansion of drought-prone conditions previously projected under regional hydroclimatic constraints scenarios.

These climatic transformations may significantly affect forage productivity, grassland stability and agricultural sustainability, especially in systems dependent on natural precipitation and semi-natural pasture ecosystems.

The combined effect of increasing temperatures and declining precipitation during the vegetation season suggests an ongoing intensification of drought risk and aridization processes in several Romanian agricultural regions.

3.4. Implications for forage systems and grassland ecosystems

Besides agroecosystems, grassland ecosystems and forage plant communities are also expected to be strongly affected. Prolonged drought periods lead to grassland desiccation, resulting in the disappearance of less drought-resistant species and their replacement by predominantly xerophilous vegetation.

Under conditions of elevated temperatures, forage species exhibit accelerated growth processes associated with reduced protein content, thereby decreasing the digestibility coefficient of vegetation. Over time, these transformations will affect the stability of grassland ecosystems, reduce

the productivity of livestock farms and ultimately contribute to land abandonment processes and losses in plant biodiversity.

Climate change also exerts profound negative effects on faunal biodiversity and entomofauna. Temperature changes increase vulnerability for more than 100 bee species and for over one-third of bumblebee species. The projected reduction in population sizes and interspecific biodiversity of beneficial agricultural entomofauna by 2100 is expected to further intensify agricultural decline under climate change conditions.

The GIS-based assessment was designed to integrate climatic, drought, land-cover and soil-related datasets in order to identify the main spatial constraints affecting Romanian agriculture and forage systems. The proposed datasets are summarized in Table 1 and include climate reanalysis data, drought indicators, land-cover products, grassland layers and administrative boundaries.

Table 1

Spatial datasets for the GIS-based assessment of climate-change constraints on Romanian agriculture and forage systems

Dataset / data source	Variable / layer	Proposed period	Spatial resolution / format	Role in the analysis
ERA5-Land monthly averaged data	2 m air temperature; total precipitation	1991–2020; 2021–2025	0.1° × 0.1° regular grid / raster	Calculation of mean temperature and precipitation during the vegetation season; identification of recent climatic anomalies
European Drought Observatory	Drought indicators, especially Combined Drought Indicator	Recent drought years / available time intervals	Raster / map layers	Identification of drought-prone areas and interpretation of agricultural exposure to drought
CORINE Land Cover	Agricultural land, pastures, heterogeneous agricultural areas	2018 reference year	Raster 100 m / vector; MMU 25 ha	Identification of agricultural and grassland-related land-cover classes
Copernicus High Resolution Layer Grasslands	Temporary and permanent grasslands; grassland change	Latest available product	High-resolution raster; grassland change product available at 20 m	Delimitation of grassland surfaces relevant for forage systems
Eurostat GISCO / NUTS boundaries	National and regional administrative boundaries	Latest available version	Vector polygon layers: SHP / GeoJSON / GDB	Clipping of datasets to Romania and aggregation of indicators by region or county
ESDAC / LUCAS topsoil physical properties	Soil texture; available water capacity	Static soil dataset	500 m raster	Interpretation of soil-related vulnerability to water deficit
Romanian administrative or agricultural boundaries, if available	Counties, agricultural regions or study-area boundaries	Latest available version	Vector polygon layers	Spatial reporting and cartographic representation of results

3.5. Adaptation strategies for forage species

In the context of increasing temperatures and declining precipitation during the vegetation season, the selection of forage species becomes an essential adaptation strategy for maintaining productivity and ecological stability in grassland and livestock systems. The GIS-based results

indicate that the most vulnerable areas are mainly located in lowland agricultural regions, where thermal stress and precipitation deficits overlap. Under these conditions, forage systems should rely increasingly on species with deep root systems, higher drought tolerance, good regrowth capacity and stable production under water-limited conditions (Table 2).

Table 2.

Adaptive value of selected forage species under increasing drought and thermal stress

Forage species	Functional group	Ecological preference	Drought tolerance	Adaptive value under climate change
<i>Medicago sativa</i>	Perennial legume	Deep, well-drained soils; warm lowland areas	High	Very valuable due to its deep root system, high biomass production and capacity to maintain productivity under moderate drought conditions
<i>Onobrychis viciifolia</i>	Perennial legume	Calcareous, dry to moderately dry soils	High	Suitable for low-input systems and dry grasslands; supports forage quality and is useful in drought-prone areas
<i>Dactylis glomerata</i>	Perennial grass	Mesic to moderately dry grasslands	Medium-high	Good persistence and regrowth capacity; useful in mixtures for areas affected by seasonal drought
<i>Festuca arundinacea</i>	Perennial grass	Moist to moderately dry soils; tolerant of variable conditions	High	Important for resilient forage mixtures due to tolerance to heat, drought and grazing pressure
<i>Trifolium pratense</i>	Perennial legume	Mesic grasslands and fertile soils	Medium	Valuable for forage quality and nitrogen fixation, but more sensitive to prolonged drought than deep-rooted legumes
<i>Lotus corniculatus</i>	Perennial legume	Moderately dry grasslands; low-input systems	Medium-high	Useful in extensive grasslands; tolerant of poorer soils and contributes to forage diversity and nitrogen fixation

A possible adaptation strategy is not based on the replacement of grassland vegetation with a single drought-resistant species, but on the use of complex forage mixtures. Mixtures combining deep-rooted legumes, such as *Medicago sativa* and *Onobrychis viciifolia*, with persistent perennial grasses, such as *Dactylis glomerata* and *Festuca arundinacea*, may increase the stability of forage production under drought and heat stress. These mixtures can improve soil cover, reduce erosion risk, maintain forage quality and enhance the resilience of livestock systems.

In more humid or mesic areas, *Trifolium pratense* remains valuable due to its high forage quality and nitrogen-fixing capacity, but its use should be adapted to local water availability. In drier regions, particularly in southern, south-eastern and western lowland areas identified by the GIS analysis as more vulnerable, greater attention should be given to drought-tolerant legumes and grasses. Therefore, forage adaptation should be spatially differentiated, taking into account regional climatic constraints, soil water availability and the expected intensification of aridization processes.

CONCLUSIONS

The GIS-based assessment highlighted a generalized increase in mean air temperatures and a reduction in precipitation amounts during the vegetation season across several agricultural regions of Romania. The strongest warming signals and the most pronounced precipitation deficits were identified mainly in southern, south-eastern and western lowland regions, confirming the ongoing intensification of aridization processes.

The obtained spatial patterns are consistent with climatic projections provided by Romanian meteorological institutions and indicate an increasing vulnerability of agricultural and forage systems to drought and thermal stress. Grassland ecosystems and forage production systems are expected to be particularly affected through reduced biomass productivity, changes in floristic composition and increasing dominance of xerophilous vegetation.

The study also demonstrates the usefulness of GIS-based climatic analyses for identifying climate-vulnerable agricultural regions and for supporting adaptation planning. In this context, the selection of drought-tolerant forage species, together with the use of resilient forage mixtures and improved water-management strategies, represents an important adaptation measure for maintaining the ecological and productive stability of Romanian grassland systems.

A limitation of the present study is represented by the relatively short recent climatic interval (2021–2025), which was used primarily to identify recent spatial tendencies rather than long-term climatic normals. In addition, the spatial resolution of ERA5-Land datasets may smooth local climatic variability in complex mountainous terrains.

Future studies should integrate longer climatic time series, higher spatial-resolution datasets and additional drought-related indicators in order to improve the assessment of agricultural vulnerability under climate change scenarios.

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