Research Journal of Agricultural Science, 58 (2), 2026; ISSN: 2668-926X;

http://doi.org/10.59463/RJAS.2026.2.37

GEOLOGICAL, CLIMATIC AND HYDROLOGICAL CONTROLS ON SOILS AND FORESTS IN GEOAGIU

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Abstract. *This study provides an integrated analysis of the geological, climatic, and hydrological conditions in the Geoagiu area (Hunedoara County, Romania), highlighting their role in soil formation and the distribution of forest vegetation. The study area is characterized by a complex geographical setting, located at the intersection of the Western Carpathians, the Transylvanian Depression, and the Southern Carpathians, which results in a high diversity of natural conditions. From a geological perspective, the lithological substrate is highly diverse, including volcanic, sedimentary, and metamorphic rocks, as well as alluvial deposits, leading to significant variations in soil properties. The climate is temperate continental, with an average annual temperature of approximately 10.1°C and average annual precipitation of about 578 mm (Deva meteorological station), characterized by pronounced seasonal variability. The hydrological regime is influenced by the Mureș River basin and a dense hydrographic network, with a nival–pluvial and percolative regime. The analysis indicates that Cambisols are the dominant soil type (approximately 79%), followed by Luvisols and other soil types in smaller proportions. Pedogenetic relationships reveal a direct correlation between parent material, climatic conditions, and vegetation types: basic substrates favor the development of fertile soils and productive forest stands, whereas acidic rocks lead to less fertile soils and lower vegetation productivity. The results emphasize the importance of the interaction between natural factors in shaping forest ecosystems and highlight the need for sustainable management practices to preserve soil resources and maintain ecological stability in the studied area.*

Keywords*: soil formation; lithology; climate variability; hydrological regime; forest ecosystems; pedogenesis*

INTRODUCTION

The soil represents a complex natural system, the result of the interaction between fundamental pedogenetic factors such as the bedrock, climate, relief, hydrological regime and vegetation (BRADY & WEIL, 2016; MIRCOV ET AL., 2025). These factors control both soil formation and evolution processes and vegetation distribution, especially in forest ecosystems, where soil–climate–rock relationships are particularly close (BUOL ET AL., 2011).

Globally, studies show that geological and lithological variability determine the differentiation of the physicochemical properties of soils, directly influencing the fertility and support capacity of vegetation (FAO, 2015; WRB, 2015). Basic rocks (basalts, marls) generate more fertile soils, while acidic or metamorphic rocks lead to poorer and more acidic soils (BRADY & WEIL, 2016).

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Climate is a major determinant of pedogenetic processes, influencing the rate of rock alteration, organic matter decomposition, and soil water regime (LAL & STEWART, 2010; MHUT & NIȚĂ, 2014). Temperatures and precipitation control the distribution of forest and grassland vegetation, as well as the dynamics of biochemical processes in the soil (BONAN, 2008; MIRCV ET AL., 2025). In continental temperate zones, characterized by accentuated seasonal variations, these processes are strongly influenced by thermal amplitudes and rainfall (PEEL ET AL., 2007).

The hydrological regime plays an essential role in the transport of substances, in the processes of eluviation and alluvial accumulation and in the development of soil horizons (HILLEL, 2004). Water availability also determines vegetation types and the productivity of forest ecosystems (WARDLE, 2002).

The relief, through altitude, exposure and inclination, influences the distribution of solar radiation, temperature and humidity, leading to spatial differentiations of soils and vegetation (MIHUȚ ET AL., 2024; MIRCOV ET AL., 2025). In mountainous and hilly areas, these variations determine the appearance of distinct topoclimates, which condition the structure and composition of forest ecosystems.

In Romania, the relationships between pedogenetic factors and soils have been intensively studied, highlighting the decisive role of the lithological substrate and climatic conditions in the formation of the main soil types (FLOREA & MUNTEANU, 2012; MUNTEANU ET AL., 2014). In the western part of the country, characterized by high geomorphological diversity, these relationships are particularly evident.

The area of Geoagiu locality (Hunedoara County) is a relevant example of complex interaction between natural factors, being located at the contact between major geomorphological units and characterized by a great geological and climatic diversity.

This diversity causes a high variability of soils and forest vegetation, which justifies a detailed study of the geological, hydrological and climatic conditions in the area.

The purpose of the work is the integrated analysis of the geological, hydrological and climatic conditions in the Geoagiu area and the evaluation of their role in the formation of soils and forest vegetation.

In this study, a characterization of the geological and lithological framework is carried out, the analysis of the climatic regime (Deva Meteorological Station), the evaluation of the hydrological conditions, the highlighting of the rock-soil-vegetation relationship, the performance of a descriptive statistical analysis of the main natural factors.

From a practical point of view, the results of this study are of particular relevance for the sustainable management of forest resources. Understanding the relationships between rock, soil and vegetation allows forest species to adapt to seasonal conditions, optimize land use and prevent soil degradation processes. At the same time, the high variability of natural factors highlights the need for a differentiated approach in ecosystem management, depending on local specificities.

MATERIAL AND METHODS

The study was carried out in the Geoagiu area, located in the central-western part of Romania, in Hunedoara County, in a complex geographical context characterized by the interference between major geomorphological units. This positioning determines a high variability of natural conditions, which provides an appropriate framework for the integrated analysis of the relationships between pedogenetic factors.

The natural setting of the studied area is dominated by a hilly and mountainous relief, with variable altitudes, which influences the distribution of temperature, precipitation and

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water regime. The geological substrate is characterized by a high lithological diversity, including volcanic, sedimentary, metamorphic rocks and alluvial deposits, each of which specifically contributes to the formation of soils.

The data used in the study were obtained through a combination of field methods and laboratory analyses, complemented by the processing of climatic and hydrological data. The investigation of the soils was carried out through pedological mapping, which involved the identification and description of the soil profiles in the field, as well as the collection of samples for further analysis. The profiles were described from a morphological point of view, following the characteristics of the horizons, texture, structure and other relevant elements for the interpretation of pedogenetic processes.

The laboratory analyses aimed to determine the main physicochemical indicators of the soil, such as soil reaction, organic matter content and nutrients, using standardised methods specific to pedology. These analyzes allowed the evaluation of soil fertility and its correlation with natural factors.

The climatic data were processed based on the records from the Deva meteorological station, the average monthly and annual temperatures and precipitation being analyzed. These data were used to characterize the climate regime and to assess its influence on pedogenetic processes and vegetation.

As regards the hydrological regime, the analysis was based on the characteristics of the river basin network and seasonal variations in flows, with a focus on the role of water in soil formation and evolution processes. The percolative regime was analysed in the context of its influence on the migration of substances in the soil profile.

The data processing included a descriptive statistical analysis, through which the mean values, variation ranges and relationships between natural factors were evaluated. In addition, graphical representations were made that allowed to highlight the correlations between climate variables and soil properties, contributing to an integrated interpretation of the results.

The methodology adopted aimed to integrate all this information into a coherent model, highlighting the relationships between rock, climate, hydrology and soil, as well as their impact on forest vegetation.

RESULTS AND DISCUSSIONS

Geological structure and pedogenetic implications

The Geoagiu area is distinguished by a high lithological complexity, determined by the overlapping of several geological formations belonging to different tectonic units. This diversity is directly reflected in the variability of soils and, implicitly, in the distribution of forest vegetation. To highlight these relationships, the main types of rocks and their pedogenetic role are summarized in Table 1.

Table 1.

Main geological formations and pedogenetic significance

Nr.crt.	Rock type	Lithological examples	Predominant location	Pedogenetic role
1	Volcanic rocks	Basalts	Almașul Mic – Poiana	Formation of fertile soils
2	Sedimentary rocks	Marls, sandstones, clays	Hilly areas	Variable fertility soils
3	Carbonate rocks	Limestones	Balșa – Ardeu	Formation of basic soils (Rendzinas)
4	Alluvial deposits	Sands, gravels	Mureș terraces	Young and productive soils
5	Metamorphic rocks	Schists, gneiss	Southern sector	Acid and low fertility soils

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The analysis of the data presented in Table 1 highlights the fact that the lithological substrate is the determining factor of soil properties, directly influencing the chemical reaction, nutrient content and its structure. Basic volcanic and sedimentary rocks favor the development of eutricbosols, characterized by high fertility and a good capacity to support productive forest vegetation. In contrast, metamorphic rocks cause the appearance of acidic distrimbosols, with reduced availability of nutrients, which leads to lower forest productivity.

This direct relationship between the bedrock and the soil confirms the fundamental role of the geological substrate in pedogenesis and explains the spatial differentiation of the forest ecosystems in the studied area.

Altitudinal structure and control over ecosystems

The relief is an essential factor in the spatial organization of soils and vegetation, through its influence on temperature, precipitation and water circulation. The altitudinal distribution of the forest area is shown in Table 2.

Table 2.

Altitudinal distribution of forest area

Altitude range (m)	**Area (ha)**	**Percentage (%)**
100–200	53.02	<1
201–400	606.31	5
401–600	3324.13	25
601–800	1866.79	14
801–1000	2826.59	21
1001–1200	2599.30	20
1201–1400	1548.46	12
1401–1600	398.01	3
Total	**13222.61**	**100**

The altitudinal distribution highlights the predominance of the range 401–600 m, which indicates a hilly-submontane character of the area. This area is associated with moderate climatic conditions and relatively fertile soils, favorable for the development of deciduous and deciduous mixtures. As the altitude increases, a reduction in soil fertility is observed, determined by the intensification of washing and acidification processes, at the same time as a decrease in temperatures. Under these conditions, the vegetation is dominated by beech trees and, at higher altitudes, by spruces. Thus, altitude acts as a control factor over the soil-vegetation relationship, generating a clear ecological layering.

Climate regime analysis

The climatic regime of the Geoagiu area is characterized by a marked seasonal variability, specific to the temperate-continental climate. The evolution of the monthly average temperatures is illustrated in Figure 1.

The distribution of average monthly temperatures shown in Figure 1 clearly highlights the temperate-continental character of the climate in the Geoagiu area. A progressive increase in temperatures from the cold to the warm season is observed, with a maximum in July and a minimum in January. The high annual thermal amplitude reflects the pronounced continental influence, which controls the dynamics of biological processes in the soil

During the vegetation period, moderate temperatures favor the activity of microorganisms and humification processes, contributing to the accumulation of organic matter. At the same time, cold periods limit these processes, leading to a relative conservation of organic carbon in the soil.

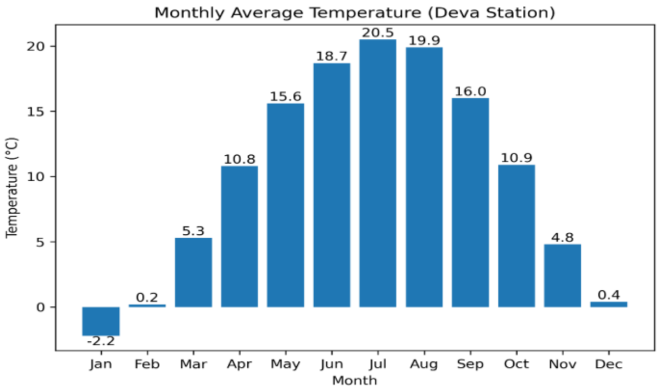

Figure 1. Monthly Average Temperature (Deva Station)

The average monthly rainfall is shown in Figure 2, highlighting their uneven distribution.

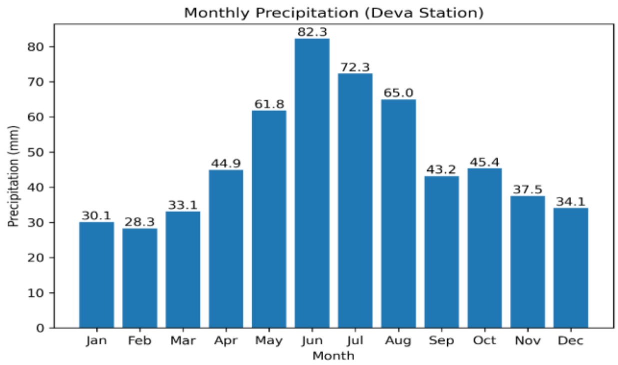

Figure 2. Monthly Precipitation (Deva Station)

Figure 2 highlights the uneven distribution of precipitation throughout the year, characterized by a maximum in the warm season and a minimum in the cold period. This distribution is specific to the temperate-continental climate and has direct implications on pedogenetic processes. High rainfall in the summer months favours eluviation and flooding processes, helping to differentiate soil horizons, while periods of low rainfall can limit the availability of water in the soil. Thus, the rainfall regime influences both the evolution of soils and the productivity of forest vegetation.

The integrated climate graph (Figure 3) provides a picture of the interaction between temperature and precipitation, highlighting the climatic regime specific to the Geoagiu area. There is a clear seasonal correlation between the increase in temperatures and the intensification of rainfall, with maximum values in the summer period, especially in June and July. This overlap of thermal and rainfall maximums is an essential factor for the development of forest vegetation, as it simultaneously provides thermal energy and water resources during the vegetation period.

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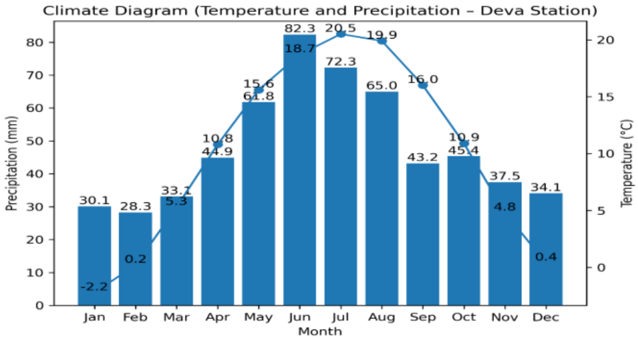

Figure 3. Climate Diagram (Temperature and Precipitation – Deva Station)

At the same time, the seasonal distribution reveals a contrast between the cold season, characterized by low temperatures and low rainfall, and the warm season, when conditions become favorable for biological processes in the soil. This alternation determines an annual rhythm of pedogenetic processes, in which the warm period favors the mineralization of organic matter and the mobilization of nutrients, while the cold period contributes to their accumulation and preservation.

From a pedological perspective, the combination of moderate temperatures and sufficient rainfall in the growing season favors the processes of eluvier and flooding, leading to the formation of evolved soils, especially cambisols and luvisols. At the same time, relatively balanced rainfall values throughout the year reduce the risk of severe droughts, which contributes to the stability of forest ecosystems.

Therefore, Figure 3 confirms that the climatic regime in the Geoagiu area is favorable to the development of forest vegetation and pedogenetic processes, but also variable enough to generate spatial differentiations of soils and ecosystems.

Figure 4 highlights the relationship between temperature and precipitation, providing insight into the interdependence of climatic factors controlling pedogenetic processes. The distribution of points shows a general trend of positive correlation, in which the increase in temperature is associated with higher precipitation values, especially in the warm season.

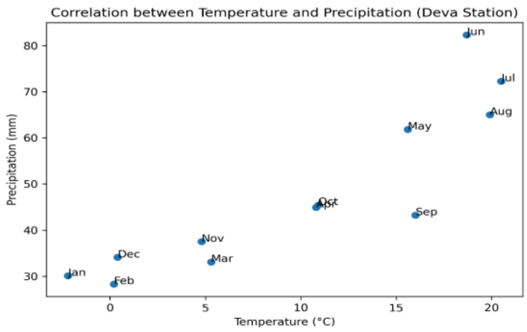

Figure 4. Correlation between Temperature and Precipitation (Deva Station)

This correlation reflects the temperate-continental climatic character of the Geoagiu area, where the vegetation period coincides with the maximum availability of water resources. The summer months (June–August) cluster in the upper area of the graph, indicating optimal conditions for biological processes in the soil, including organic matter mineralization and nutrient mobilization.

In contrast, the winter months are characterized by low temperatures and low rainfall, being concentrated at the bottom of the graph. These conditions limit microbiological activity and slow down pedogenetic processes, contributing to the accumulation of organic matter.

From a pedological point of view, this climate-climate relationship (temperature-precipitation) is indirectly reflected in the properties of the soil, influencing the humidity regime, the eluviation and alluvial processes and, implicitly, the differentiation of soil horizons. The observed correlation supports the development of cambisols and luvisols, characteristic of areas with balance between water intake and thermal energy.

Therefore, Figure 4 confirms that climatic factors act synergistically in the control of pedogenesis, and their seasonal variations determine the dynamics of soils and forest ecosystems.

Figure 5 highlights the relationship between rainfall and a soil fertility index, providing an integrated perspective on how climate influences edaphic properties. The distribution of the points indicates a clear trend of positive correlation, in which the increase in the amount of precipitation is associated with higher values of soil fertility.

This relationship reflects the essential role of water in pedogenetic processes, especially in terms of nutrient mobilization, microbiological activity and organic matter dynamics. In the months of high rainfall, corresponding to the growing season, maximum fertility values are observed, which indicates favorable conditions for mineralization processes and the availability of nutrients for plants.

On the other hand, during periods of low rainfall, soil fertility is lower, as a result of limiting biological processes and nutrient mobility. This seasonal variability highlights the direct dependence of soil functioning on the water regime.

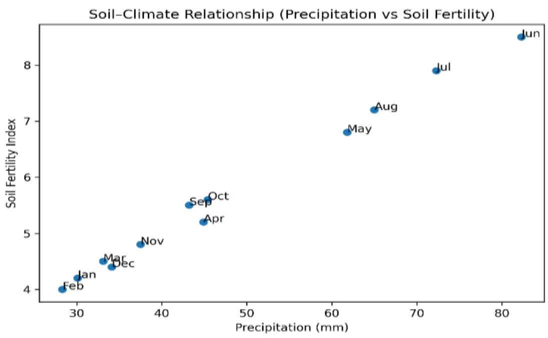

Figure 5. Soil–Climate Relationship (Precipitation vs Soil Fertility)

From a pedological point of view, the observed relationship confirms that precipitation controls the processes of eluviation and alluvialization, influencing the distribution of clay and nutrients in the soil profile. In the climatic conditions of the Geoagiu area, this mechanism favors the development of cambisols and luvisols, characterized by a balance between the processes of accumulation and loss of substances.

Figure 5 therefore shows that climatic factors, in particular rainfall, play a decisive role in controlling soil fertility and its evolution, contributing to the structuring of forest ecosystems and their functional stability.

Therefore, the climate acts simultaneously as a favorable and limiting factor in the evolution of soils.

The relationship between rock, soil and vegetation

The interdependence between the lithological substrate, soil and vegetation is summarized in Table 3, which highlights the fundamental pedogenetic relationships in the studied area.

Table 3.

Rock–soil–vegetation relationships

Rock type	**Soil type**	**Dominant vegetation**
Basalts, marls	Eutric Cambisols	Beech, mixed forests
Limestones	Rendzinas	Calcicolous vegetation
Sandstones, clays	Luvisols	Beech, oak
Schists, gneiss	Distric Cambisols	Spruce, beech
Alluvial deposits	Alluvial soils	Grassland, mixed vegetation

The data presented in Table 3 highlight that the lithological substrate controls the chemical properties of the soil, while climate and hydrology modulate the pedogenetic processes. The vegetation thus appears as a faithful indicator of ecological conditions, directly reflecting the characteristics of the soil.

This functional relationship can be described as a dynamic system in which each component influences and is influenced by the others, generating an ecological balance specific to each landscape unit.

Synthesis and interpretation of the ecological system

The integrated analysis of natural factors highlights the existence of a complex ecological system, characterized by a high variability, but also by a significant degree of stability. Average temperature and precipitation values, together with lithological and altitudinal diversity, create favorable conditions for the development of evolved soils and forest ecosystems. The dominance of cambisols reflects an intermediate stage of pedogenetic evolution, specific to temperate conditions, where the processes of alteration and accumulation are balanced. At the same time, the altitudinal distribution and variability of the substrate determine important local differentiations, which influence the productivity of ecosystems.

The results obtained demonstrate the existence of a direct correlation between altitude, climate, soil and vegetation, confirming the integrated character of the natural system in the Geoagiu area. This interdependence highlights the importance of the systemic approach in the study of soil resources and underlines the need for management strategies adapted to local conditions.

The results obtained in this study highlight the deeply integrated character of the relationships between the natural factors and the pedogenetic processes in the Geoagiu area, confirming that the soil represents a direct expression of the interaction between the geological substrate, the climatic conditions and the hydrological regime.

Compared to the studies conducted globally, the results confirm the general trend according to which the lithological substrate directly controls the fertility of the soil and its typology. Thus, the base rocks identified in the Geoagiu area favor the development of soils with neutral or weak alkaline reaction and with a higher capacity to support vegetation. In contrast, metamorphic and acidic rocks lead to the emergence of poorly evolved soils with reduced acid reaction and fertility, which is directly reflected in the lower productivity of forest ecosystems.

From a climatic perspective, the temperate-continental regime characteristic of the studied area fits into the patterns described in the literature for the temperate regions of Central and Eastern Europe. The values of the average annual temperature and the seasonal distribution of precipitation are comparable to those reported in global climate studies, which confirms that the pedogenetic processes observed in Geoagiu are representative for this bioclimatic zone. At the same time, the positive correlation between temperature and precipitation, highlighted in the graphical analysis, supports the idea that the vegetation period coincides with the maximum availability of resources, favoring biological processes in the soil.

The results on the hydrological regime confirm the essential role of water in the processes of soil formation and evolution, in line with the conclusions formulated in the field of soil physics and hydropedology. The dominant percolative regime causes the migration of substances in the soil profile, favoring the eluviation and alluvial processes and contributing to the differentiation of genetic horizons. This dynamic is comparable to that described in European studies on luvisols and cambisols, where the distribution of water in the profile plays a decisive role in their evolution.

Regarding the relationship between climate and soil fertility, the correlational analysis highlights a direct dependence between the rainfall regime and the intensity of biological processes. This observation is supported by studies on biogeochemical cycles, which show that water availability controls microorganism activity and nutrient dynamics. In this context, the results obtained in the Geoagiu area indicate that periods of high precipitation coincide with the intensification of mineralization processes, which contributes to increasing soil fertility.

At national level, the results are in line with the pedological research carried out in Romania, which highlights the predominance of cambisols in hilly and mountainous areas, as well as the decisive influence of the lithological substrate and climatic conditions on their formation. At the same time, the altitudinal distribution of soils and vegetation in the Geoagiu area confirms the general trends observed in the Romanian Carpathians, where the altitudinal leveling determines a clear succession of ecosystem types.

CONCLUSIONS

The integrated analysis of geological, climatic, and hydrological conditions in the Geoagiu area demonstrates that soil formation and forest vegetation are controlled by the interaction of multiple natural factors. Lithological diversity, including volcanic, sedimentary, and metamorphic rocks, plays a decisive role in differentiating soil properties, influencing pH, fertility, and vegetation support capacity.

The results indicate that basic substrates favor the development of more fertile soils, particularly eutric cambisols, which sustain productive forest ecosystems, whereas acidic rocks lead to less fertile soils with reduced nutrient availability. These findings confirm the primary influence of the parent material on soil characteristics and ecosystem distribution.

Climatic conditions regulate biological activity and organic matter dynamics, while the hydrological regime, dominated by percolation processes, contributes to the redistribution of substances and the differentiation of soil horizons. These combined effects explain the predominance of cambisols and the moderate stage of soil development in the study area.

The strong interdependence between rock, soil, climate, and vegetation highlights the existence of a relatively balanced ecological system, in which vegetation reflects the underlying pedoclimatic conditions.

In the context of climate change, these relationships require continuous monitoring and adaptive management strategies to maintain ecosystem resilience and soil functionality.

http://doi.org/10.59463/RJAS.2026.2.37

Overall, the Geoagiu area represents a complex and stable pedo-ecological system, whose dynamics justify further research on soil evolution and sustainable land use.

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