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Soil–relief–vegetation interactions in the Caatinga domain: geoenvironmental controls in the brazilian semiarid with application to Serra do Lima, Patu–RN

Interações solo–relevo–vegetação no domínio das Caatingas: condicionantes geoambientais no semiárido brasileiro com aplicação na Serra do Lima, Patu-RN

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Abstract: The Caatinga Domain, in the Brazilian semiarid region, is characterized by pronounced geoenvironmental heterogeneity resulting from the interaction among climate, geological substrate, relief, soils, and vegetation cover. Although traditionally described based on physiognomic and floristic criteria, the Caatinga exhibits spatial patterns strongly conditioned by pedogeomorphic controls and altitudinal gradients, particularly in mountainous environments and areas with rocky outcrops. This study aims to analyze soil–relief–vegetation interactions within the Caatinga Domain, identifying the main geoenvironmental controls responsible for landscape organization, with application to Serra do Lima, Patu–RN. The methodological approach was based on a systematic and analytical review of the scientific literature, articulating official vegetation classifications with frameworks that incorporate geomorphological, lithological, and pedological variables. The results indicate that soil attributes, water availability, slope gradient, hillslope position, and substrate nature exert a decisive influence on the distribution and structure of plant physiognomies, including rupestrian formations associated with granitic outcrops. It is concluded that vegetation dynamics in the semiarid region cannot be fully understood through exclusively descriptive classifications, requiring an integrated approach to the landscape, capable of incorporating geoenvironmental controls into ecological interpretation and environmental management of the biome.

Keywords: Rock outcrops; Rupicolous vegetation; Phytosociology; Soil nutrients; Soil acidity.

Resumo: O Domínio das Caatingas, no semiárido brasileiro, caracteriza-se por elevada heterogeneidade geoambiental, resultante da interação entre clima, substrato geológico, relevo, solos e cobertura vegetal. Embora tradicionalmente descrita com base em critérios fisionômicos e florísticos, a Caatinga apresenta padrões espaciais fortemente condicionados por controles pedogeomorfológicos e por gradientes altitudinais, particularmente em ambientes serranos e setores com afloramentos rochosos. Este estudo objetiva analisar as interações solo–relevo–vegetação no Domínio das Caatingas, identificando os principais condicionantes geoambientais responsáveis pela organização da paisagem, com aplicação na Serra do Lima, em Patu–RN. A abordagem metodológica fundamentou-se em revisão sistemática e analítica da literatura científica, articulando classificações oficiais da vegetação com abordagens que incorporam variáveis geomorfológicas, litológicas e pedológicas. Os resultados indicam que atributos do solo, disponibilidade hídrica, declividade, posição na vertente e natureza do substrato exercem influência decisiva sobre a distribuição e a estrutura das fitofisionomias, incluindo formações rupestres associadas a afloramentos graníticos. Conclui-se que a dinâmica da vegetação no semiárido não pode ser plenamente compreendida a partir de classificações exclusivamente descritivas, sendo necessária uma abordagem integrada da paisagem, capaz de incorporar os controles geoambientais na interpretação dos padrões ecológicos e na gestão ambiental do bioma.

Palavras-chave: Afloramentos rochosos; Vegetação rupestre; Fitossociologia; Nutrientes; Acidez.

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1. Introduction

The Caatinga Morphoclimatic Domain occupies extensive areas of the Brazilian semiarid region and is characterized by high mean annual temperatures, strong rainfall irregularity, and marked climatic seasonality, with precipitation concentrated in a short period of the year and a prolonged dry season (Veloso; Góes-Filho, 1982; Ab'Sáber, 2003; Silva; Cruz, 2018). These climatic conditions impose severe hydrothermal constraints, exerting direct control over the geomorphological, pedological, and ecological processes that structure the regional landscape.

In the semiarid context, surface dynamics are marked by the predominance of generally shallow, stony, and poorly developed soils, frequently associated with crystalline substrates and dissected relief (Corrêa; Souza; Cavalcanti, 2014; Souza et al., 2023; Santos et al., 2023; Hilário et al., 2024; Santos et al., 2026). Although historically associated with a homogeneous landscape, the Caatinga reveals remarkable heterogeneity, with diverse phytophysiognomies (Veloso; Góes-Filho, 1982; Silva; Cruz, 2018; Souza et al., 2021). This variability favors the occurrence of phytogeographic enclaves associated with locally differentiated conditions of altitude, lithology, relief, and water availability (Fernandes, 2018; Silva; Cruz, 2018). Such enclaves differ structurally, functionally, and floristically from the surrounding typical formations, highlighting the decisive role of geoenvironmental controls in the organization of the semiarid landscape mosaic (Silva; Cruz, 2018; Borges Neto et al., 2025).

Caatinga vegetation presents high physiognomic and floristic diversity, composed of hypo-, xero-, and hyperxerophilous species endowed with morphophysiological adaptations to prolonged water deficit (Veloso; Góes-Filho, 1982; Freire et al., 2018; Silva; Cruz, 2018; Souza et al., 2021). Among these adaptive strategies, seasonal leaf deciduousness, microphyllous leaves, spinescent structures, rhizomes, water storage tissues, and broad structural plasticity stand out, encompassing formations ranging from arboreal to shrubby and grassy-woody types (Guedes, 2023). These characteristics reflect integrated responses to the constraints imposed by climate, edaphic conditions, and topographic compartmentalization (Borges Neto et al., 2025).

In this sense, the evolution and organization of the landscape in the Caatinga Domain result from continuous interactions among soil, relief, and vegetation (Ab'Sáber, 2003; Souza et al., 2023; Santos et al., 2023; Borges Neto et al., 2025; Santos et al., 2026). Each topographic compartment expresses specific combinations of these factors, configuring distinct patterns of vegetation cover and ecosystem functioning (Veloso; Góes-Filho, 1982). Despite advances in the isolated understanding of these components, studies that systemically analyze soil–relief–vegetation interactions in the Brazilian semiarid region remain incipient. This gap becomes particularly evident in mountainous environments and along altitudinal gradients, where differentiated microenvironmental conditions may favor greater structural and floristic diversity (Giulietti, 2004; Souza et al., 2021; Borges Neto et al., 2025).

In this context, it becomes essential to consolidate a systemic geoenvironmental approach that allows the vegetation of the Caatinga to be understood as an expression of the dynamic interaction among surface processes, geological substrate, relief morphology, and edaphic differentiation, especially in altitudinal contexts. In this sense, the present article aims to analyze, from a systemic perspective, the soil–relief–vegetation interactions within the Caatinga Domain in the Brazilian semiarid region, with empirical application in Serra do Lima, in Patu, Rio Grande do Norte, Brazil.

2. Methodology

2.1. Study area

The study area corresponds to Serra do Lima, located in the municipality of Patu, Rio Grande do Norte, Brazil (Fig. 1). The geology is predominantly composed of Neoproterozoic granites of the Itaporanga Suite, associated with the Borborema Province (Angelim et al., 2006). It consists of an inselberg-type residual relief with an altimetric range varying from 166 to 650 m. The relief presents convex summits, steep escarpments, and slopes partially covered by angular blocks. In the highest sectors, domical rock outcrops predominate. The soils are mostly shallow and poorly developed, associated with the granitic basement, with predominant occurrence of Lithic Entisols and Haplic Cambisols. The climate is semiarid, with mean annual temperatures ranging from 21 °C to 28 °C, which may reach extreme values close to 38 °C (Hemetério Filho, 2005). Precipitation is irregular, averaging approximately 870 mm per year (Hemetério Filho, 2005; Lucena; Cabral; Steinke, 2018). The vegetation belongs to the Caatinga Domain and exhibits physiognomic variability (Giulietti, 2004; Oliveira, 2024).

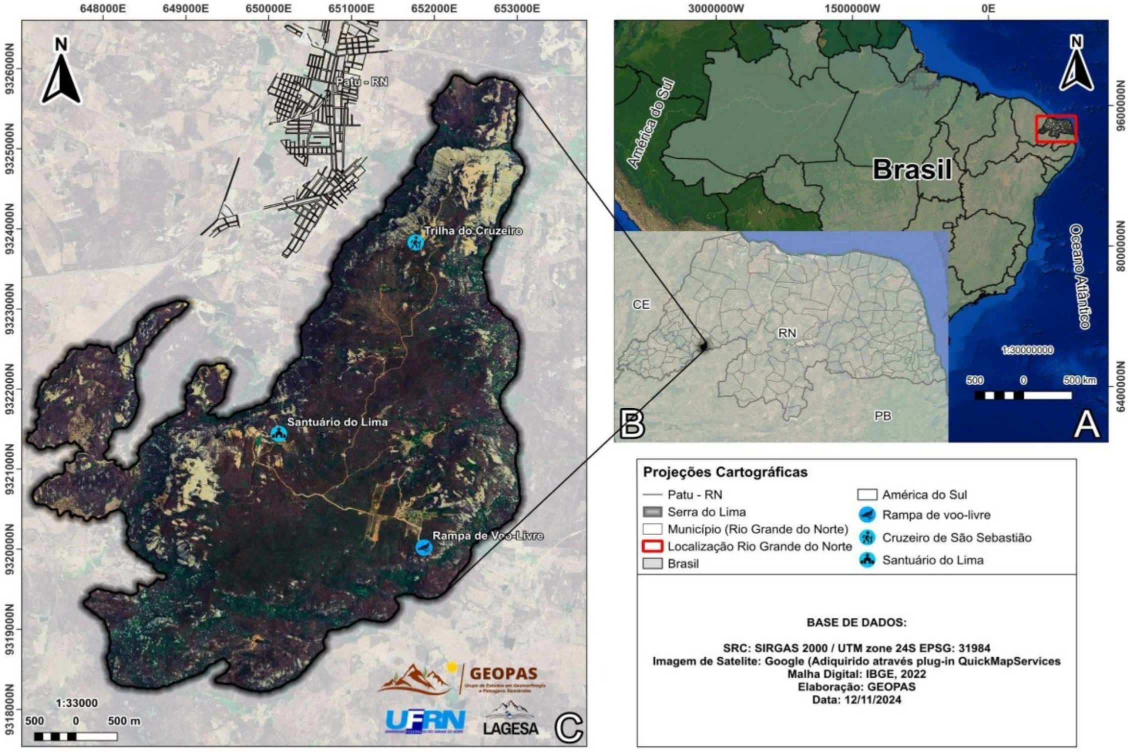


Figure 1 – Location of the state of Rio Grande do Norte (A), highlighting Patu–RN (B) and Serra do Lima (C). Source: Authors (2026).

2.2. Methodological procedures

A bibliographic survey was conducted in databases such as SciELO, Google Scholar, and the CAPES Journal Portal. The selection of studies prioritized thematic relevance, methodological consistency, academic impact, and adherence to the spatial and conceptual scope of the research. Both classical studies, responsible for consolidating the conceptual frameworks on the Caatinga and its geoenvironmental determinants, and recent research incorporating integrated approaches, multiscale analyses, and contemporary environmental interpretation techniques were considered. The selected materials were subjected to critical reading and interpretative analysis, which made it possible to identify convergences, gaps, and conceptual divergences, particularly regarding the classifications of Caatinga vegetation.

Within the scope of the comparative analysis, the official classifications of Brazilian vegetation proposed by the Brazilian Institute of Geography and Statistics (IBGE, 2012) were examined in contrast with approaches that explicitly incorporate geoenvironmental determinants, particularly geomorphological and pedological aspects, such as the systematization proposed by Cavalcanti (2014). Based on this comparison, a conceptual and classificatory adaptation was carried out in order to improve the analytical coherence of the study and to strengthen the articulation among vegetation, soils, and relief in the semiarid context. The data extracted from the literature were organized according to thematic and hierarchical criteria, resulting in the elaboration of summary tables, comparative tables, and conceptual schemes that support the discussion on the different types of Caatinga vegetation and their relationships with aspects of the physical environment.

In addition to the bibliographic review, a case study was developed in Serra do Lima, municipality of Patu–RN (Fig. 1). The investigation involved field surveys for the physiognomic characterization of the vegetation, identification of plant species, observations of topographic position, slope analysis, identification of rock outcrops, and preliminary soil description. The characterization of vegetation cover was initially carried out based on phytophysiognomic criteria associated with the morphopedological conditions observed in loco. Subsequently, based on the data obtained in the field, plant species were identified with the aid of dichotomous keys (Flora do Brasil, 2020), and the nomenclature was validated in digital repositories such as Tropicos® (Missouri Botanical Garden). Finally, the results of the review and the case study were integrated under a systemic landscape perspective, understanding Caatinga vegetation as an expression of the dynamic interaction among climatic, geomorphological, pedological, and biological factors.

3. Results and Discussion

3.1 Terminologies of Caatinga vegetation

The systematization of knowledge concerning the vegetation of the Caatinga biome in Brazil has as its structuring milestone the RADAMBRASIL Project (1971–1985), responsible for integrated surveys of natural resources at the national scale. Within this project, phytogeographic studies were conducted under the coordination of H. P. Veloso, whose contribution was decisive for the terminological and cartographic standardization of Brazilian vegetation cover (Cavalcanti, 2024). Based on the frameworks established by RADAMBRASIL, the predominant vegetation in the Caatinga Domain came to be officially classified as Steppe, a denomination later incorporated by the Brazilian Institute of Geography and Statistics (IBGE). This classification was based on an analogy with the Wooded and/or Shrub Steppe (steppe arborée et/ou arbustive), emphasizing structural attributes such as seasonal leaf deciduousness, the presence of thorny shrubs, and the development of a seasonal herbaceous layer (Veloso; Góes-Filho, 1982; Cavalcanti, 2024).

This conceptual framework is associated with European and African phytogeographic traditions (Trochain, 1955; Veloso; Góes-Filho, 1982). In this context, the northeastern Caatinga was considered homologous to African steppe formations, particularly due to convergent morphophysiological responses to semiarid climatic conditions (Veloso; Góes-Filho, 1982; Cavalcanti, 2024). However, Caatinga vegetation has been described using multiple terminologies in both national and international literature, reflecting different theoretical frameworks, analytical scales, and research objectives. Among the recurrent denominations in Portuguese are savana-estépica, floresta seca, and mata seca, whereas in international literature the terms savane steppique, seasonally dry forest, seasonally dry tropical forest, and tropical dry forest predominate (Fig. 2).

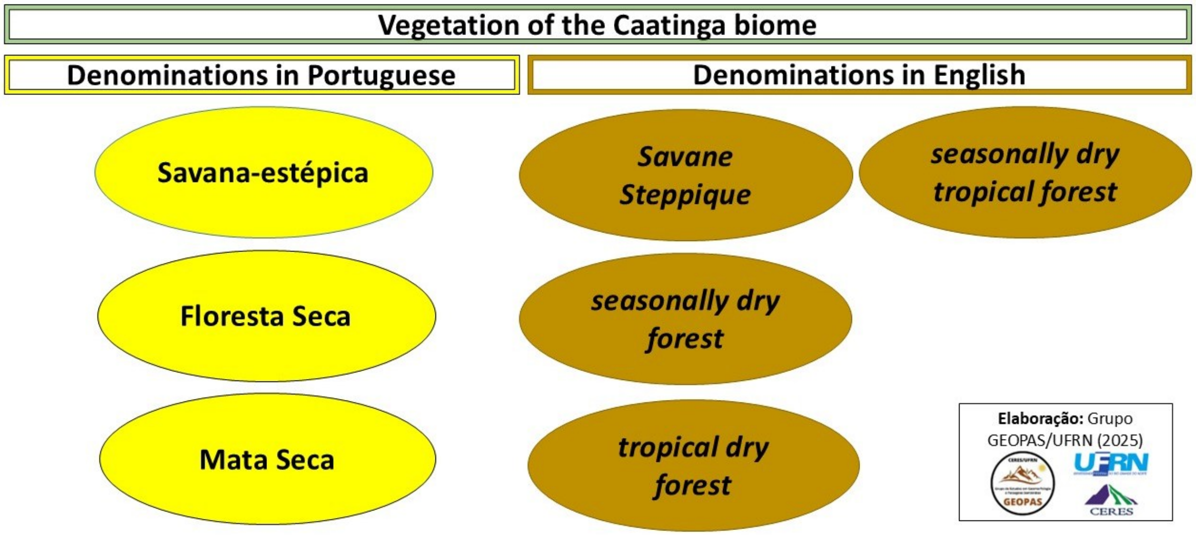


Figure 2 – Vegetation of the Caatinga biome and its usual terminologies.
Source: Authors (2026).

This terminological diversity indicates that, although many of these classifications refer to formations subjected to a similar climatic regime characterized by strong hydrological seasonality, with a short rainy season and a prolonged dry period, they are not strictly synonymous. Each denomination carries specific conceptual assumptions, particularly regarding vegetation structure, degree of arboreal development, and biogeographic classification. The term steppe savanna, officially adopted by the IBGE, emphasizes the physiognomic attributes of open formations with predominance of shrub and herbaceous elements (Trochain, 1955; Veloso; Góes-Filho, 1982). In contrast, expressions such as dry forest tend to emphasize the presence of a more developed arboreal layer, although still subject to seasonal deciduousness. Meanwhile, the terminology seasonally dry tropical forest places the Caatinga within a broader biogeographic context, approximating it to tropical forests subjected to periodic water stress (Souza et al., 2021).

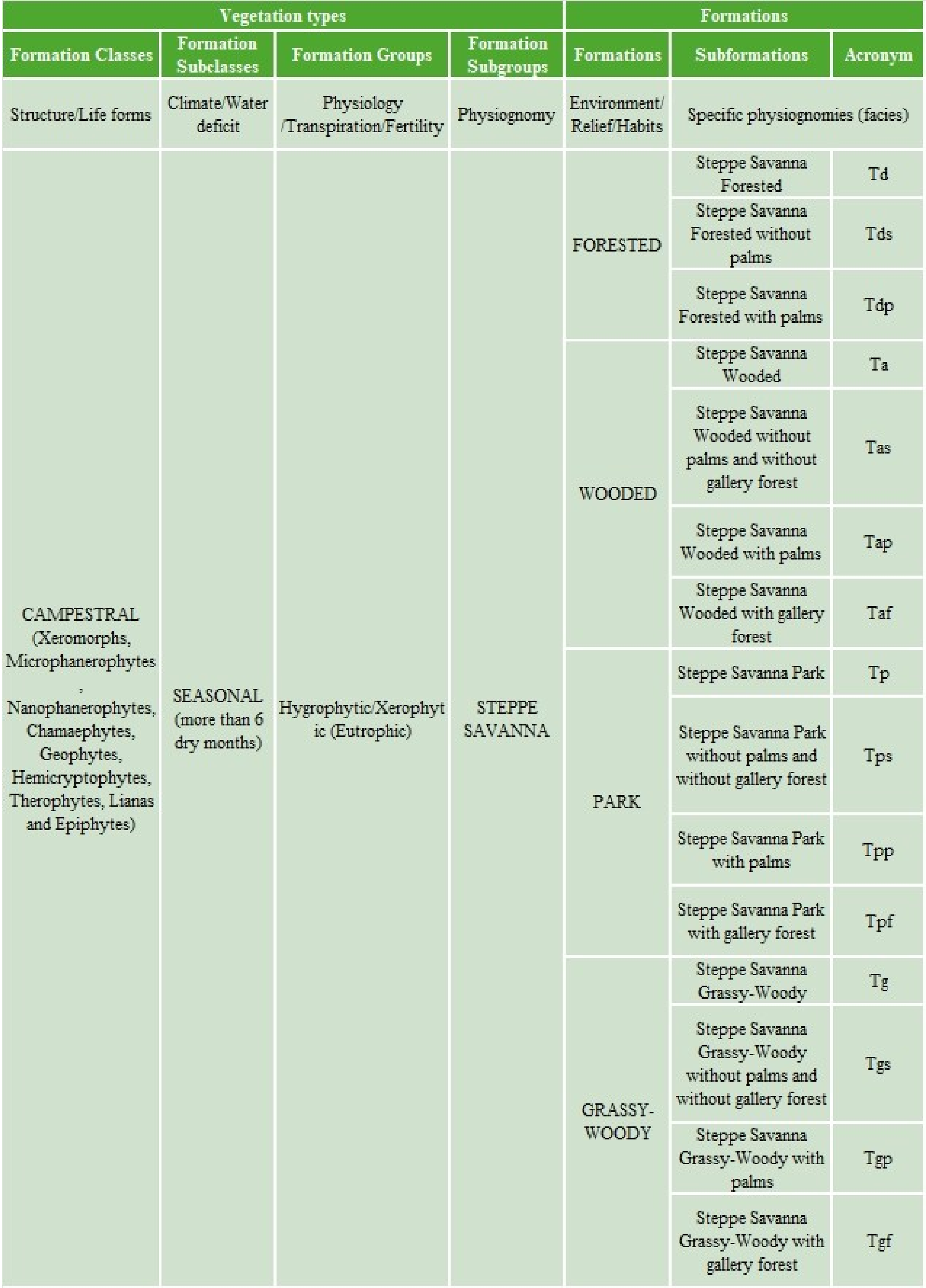
The multiplicity of nomenclatures therefore reflects not only the structural complexity of the Caatinga but also the inherent limitations of classifications based exclusively on physiognomic or floristic criteria. Several authors argue that such approaches, including the official IBGE methodology (2012), tend to treat the physical determinants of the landscape—such as relief, lithology, and soils—as secondary factors, despite their fundamental importance for understanding the spatial distribution and dynamics of vegetation formations in the semiarid region (Silva; Cruz, 2018).

In this sense, the Caatinga should not be understood as a homogeneous phytogeographic unit but rather as a mosaic of vegetation formations strongly conditioned by interactions among climate, geological substrate, pedogenesis, and relief compartmentalization (Santos et al., 2023). This perspective reinforces the need for integrated approaches capable of articulating the different terminologies with the geoenvironmental foundations of the landscape, particularly in mountainous environments and along altitudinal gradients, where physiognomic diversity tends to increase.

3.2 Vegetation types according to IBGE (2012): scope and limitations

According to the official classification proposed by IBGE (2012), the predominant vegetation in the Caatinga Domain is classified as Steppe Savanna (Savana-Estépica), subdivided into four main formations: (i) Forested; (ii) Wooded; (iii) Park; and (iv) Grassy-Woody. These formations reflect structural and physiognomic variations in vegetation cover, mainly associated with seasonal climatic regimes, water availability, and edaphic and topographic conditions (Table 1).

Table 1 – Types of Steppe Savanna vegetation and their formations.



Vegetation types				Formations		
Formation Classes	**Formation Subclasses**	**Formation Groups**	**Formation Subgroups**	**Formations**	**Subformations**	**Acronym**
Structure/Life forms	Climate/Water deficit	Physiology /Transpiration/Fertility	Physiognomy	Environment/ Relief/Habits	Specific physiognomies (facies)	
CAMPESTRAL (Xeromorphs, Microphanerophytes, Nanophanerophytes, Chamaephytes, Geophytes, Hemicryptophytes, Therophytes, Lianas and Epiphytes)	SEASONAL (more than 6 dry months)	Hygrophytic/Xerophytic (Eutrophic)	STEPPE SAVANNA	FORESTED	Steppe Savanna Forested	Td
					Steppe Savanna Forested without palms	Tds
					Steppe Savanna Forested with palms	Tdp
				WOODED	Steppe Savanna Wooded	Ta
					Steppe Savanna Wooded without palms and without gallery forest	Tas
					Steppe Savanna Wooded with palms	Tap
					Steppe Savanna Wooded with gallery forest	Taf
				PARK	Steppe Savanna Park	Tp
					Steppe Savanna Park without palms and without gallery forest	Tps
					Steppe Savanna Park with palms	Tpp
					Steppe Savanna Park with gallery forest	Tpf
				GRASSY-WOODY	Steppe Savanna Grassy-Woody	Tg
					Steppe Savanna Grassy-Woody without palms and without gallery forest	Tgs
					Steppe Savanna Grassy-Woody with palms	Tgp
					Steppe Savanna Grassy-Woody with gallery forest	Tgf

Source: IBGE (2012).

The IBGE (2012) classification is structured as a multilevel hierarchical system that articulates ecological, physiognomic, and environmental criteria (Table 1). Initially, the classification is based on the predominant life forms (xeromorphs, microphanerophytes, nanophanerophytes, chamaephytes, geophytes, hemicryptophytes, and therophytes), reflecting morphophysiological adaptations to prolonged water deficit. Subsequently, it incorporates the climatic criterion, defined as seasonal with more than six dry months, establishing the macroenvironmental framework of the vegetation. The classificatory progression advances to physiological criteria (hygrophytic/xerophytic) and fertility conditions (eutrophic), culminating in the definition of the Steppe Savanna formations themselves. Thus, the model combines structural, functional, and environmental dimensions, although the final emphasis remains predominantly on vegetation physiognomy.

Within the Steppe Savanna subgroup, the four main formations represent a structural gradient of woody vegetation density and stature, ranging from denser formations (Forested) to more open formations (Grassy-Woody) (IBGE, 2012). This arrangement suggests an integrated response to water availability and soil depth conditions. The Forested Steppe Savanna is characterized by a more continuous and taller arboreal layer, although still subject to seasonal deciduousness. Its occurrence is generally associated with environments presenting relatively deeper soils and greater moisture retention capacity, favoring more developed root systems and higher woody biomass.

The Wooded Steppe Savanna presents lower arboreal density, with more widely spaced individuals and greater participation of the shrub layer (IBGE, 2012). This configuration indicates environments with more pronounced edaphic constraints or greater susceptibility to erosive processes, where the development of a continuous canopy becomes limited. The Park Steppe Savanna is distinguished by the presence of isolated trees or small groups distributed over a relatively continuous herbaceous layer (IBGE, 2012). This formation tends to occur on flattened or gently undulating surfaces, where topographic control, combined with climatic seasonality, regulates the distribution of woody individuals. Finally, the Grassy-Woody Steppe Savanna represents the most open extreme of the structural spectrum, with predominance of the herbaceous layer and sparse occurrence of shrubs or trees (IBGE, 2012). This formation is common in areas with shallow soils, high surface stoniness, or intense water stress, reflecting more severe limitations imposed by the physical substrate.

In addition to the main formations, IBGE (2012) recognizes a set of subformations differentiated by specific physiognomic attributes, such as the presence or absence of palms and gallery forests. This differentiation introduces an important typological refinement, particularly regarding the local influence of surface water availability. The presence of gallery forest, for example, indicates the action of hydrological controls that transcend the regional climatic regime, highlighting the importance of geomorphological determinants and fluvial dynamics. However, although the classificatory system presents internal coherence and cartographic utility at the national scale, its structure remains strongly anchored in physiognomic criteria. Geomorphological, lithological, and pedological factors appear indirectly as implicit determinants of vegetation structure but do not constitute the central axis of the typology.

The adoption of the term Steppe Savanna is directly linked to the phytogeographic tradition consolidated by the RADAMBRASIL Project, whose foundations are associated with models developed for African tropical regions. In this context, the Caatinga was interpreted as homologous to steppe formations of other semiarid environments, mainly due to seasonal deciduousness, the presence of thorny shrubs, and a seasonal herbaceous layer (Cavalcanti, 2024). However, when analyzed from the perspective of soil–relief–vegetation interactions, the hierarchy proposed by IBGE proves partially limited in explaining the spatial heterogeneity observed in mountainous environments and contrasting geomorphological compartments. The transition between forested and grassy-woody formations, for example, does not always represent a continuous structural gradient but may reflect abrupt changes associated with soil properties, lithology, or relief. Thus, although the IBGE (2012) classification constitutes a fundamental reference for the national mapping of Caatinga vegetation, its application in more detailed geoenvironmental analyses requires complementary integrative approaches.

3.3 Vegetation types and their formations considering geoenvironmental conditions

Caatinga vegetation has traditionally been classified based on predominantly physiognomic and floristic criteria, as exemplified by the official IBGE methodology (2012). However, integrative classificatory proposals exist that explicitly incorporate the physical determinants of the landscape, particularly relief, soils, lithology, and hydrological dynamics. The systematization presented by Cavalcanti (2014) stands out for adopting an integrated geoenvironmental approach, in which vegetation is interpreted as a functional expression of the conditions of the physical substrate. Thus, the structure and physiognomy of vegetation formations are understood as resulting from the interaction between climatic controls and local factors such as soil depth and fertility, topographic position, slope gradient, surface stoniness, presence of rock outcrops, and proximity to water bodies (Table 2).

Table 2 – Types of Caatinga vegetation and their descriptions.

Types of Caatinga Vegetation	**Description**
Closed Arboreal	Dominated by woody species, with trees taller than 5 m. The tree canopies touch and interlock.
Open Arboreal	Dominated by woody species, with trees taller than 5 m. The tree canopies do not touch or interlock.
Sub-arboreal	Dominated by woody elements ranging from 3 to 5 m in height.
Closed Shrubland	Dominated by shrubs shorter than 3 m, densely distributed across the landscape.
Open Shrubland	Dominated by shrubs shorter than 3 m, forming open spaces within the landscape.
Grassy-Woody Vegetation	Dominated by herbaceous elements, with the presence of woody individuals (trees or shrubs) scattered or forming isolated clusters.
Hygrophilous Vegetation	Vegetation that grows near water bodies and generally presents cosmopolitan or introduced flora.
Rocky Field (Campo Rupestre)	Vegetation formation that develops among rocky outcrops. It usually shows a high level of endemism, with predominance of herbaceous-shrub species and cacti.

Source: Adapted from Cavalcanti (2014).

The integrated interpretation of photographs and conceptual diagrams indicates that each formation corresponds to a distinct morphopedological compartment, reinforcing the premise that vegetation cover heterogeneity directly reflects relief compartmentalization (Fig. 3).

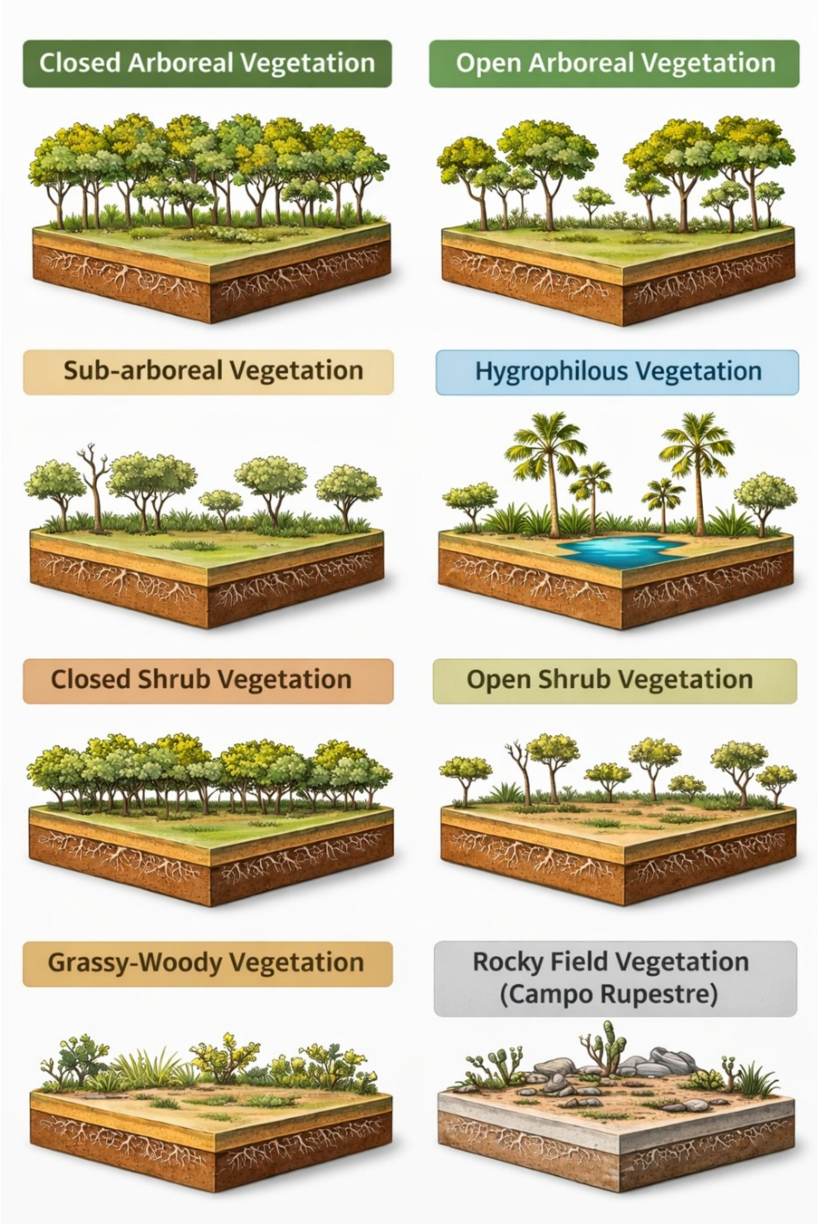


Figure 3 – Diagram blocks representing Caatinga subgroups and associated formations.
Source: Authors (2026).

Arboreal formations (closed or open) represent sectors with the greatest structural development of woody biomass. Closed arboreal formations, characterized by continuous and interlaced canopies, are associated with deeper, better-structured soils with greater water retention capacity, frequently located in intermediate topographic positions or areas of colluvial accumulation. Open arboreal formations, although maintaining heights greater than 5 m, present canopy discontinuity, reflecting greater water limitation or reduced effective soil depth.

The subarboreal formation occupies a transitional position within the structural gradient and commonly occurs on slopes with moderate gradients and moderately shallow soils. In these environments, physical substrate constraints associated with greater exposure and erosive dynamics limit the development of taller trees, favoring woody individuals between 3 and 5 m in height. Shrub formations (closed and open) demonstrate stronger edaphic and geomorphological control. Closed shrub formations tend to occur in areas where, despite water limitations, sufficient soil depth exists to sustain greater vegetation density. In contrast, open shrub formations are strongly associated with surfaces characterized by shallow soils, high stoniness, and frequent rock outcrops, configuring environments with greater water stress and greater vulnerability to erosive processes.

The grassy-woody formation represents more open structural stages, with predominance of the herbaceous layer and sparse occurrence of woody elements (Cavalcanti, 2014). This typology is associated with flattened or gently undulating surfaces presenting poorly developed soils, low water retention capacity, and sometimes surface compaction, factors that restrict the establishment of continuous shrub or arboreal canopies. Hygrophilous vegetation, in turn, constitutes an exception in the semiarid context and is directly linked to the presence of surface or subsurface water. Its occurrence along watercourses highlights the importance of local hydrological controls that create microenvironments with lower water deficit and greater nutrient availability. In these sectors, the floristic composition tends to differ significantly from adjacent formations and may include cosmopolitan or introduced species (Cavalcanti, 2014).

Rocky fields represent the most extreme expression of lithological control over vegetation. They develop on rock outcrops and extremely shallow soils, where water availability is limited and root anchorage depends on fractures and microdepressions in the rock (Cavalcanti, 2014). The high ecological specialization of these areas results in a high degree of endemism, with predominance of herbaceous–shrub species and cacti adapted to restrictive edaphic conditions.

3.4 Application of vegetation types and formations considering the geoenvironmental conditions of Serra do Lima

The application of the adapted classification proposal to the geoenvironmental conditions of Serra do Lima allowed the identification of eight main vegetation types (Fig. 4), defined through the articulation of structural criteria and morphopedological variables. The analysis shows that each vegetation formation corresponds to specific relief compartments, reinforcing the central hypothesis of this study that vegetation cover heterogeneity directly reflects the geomorphological and pedological compartmentalization of the landscape.

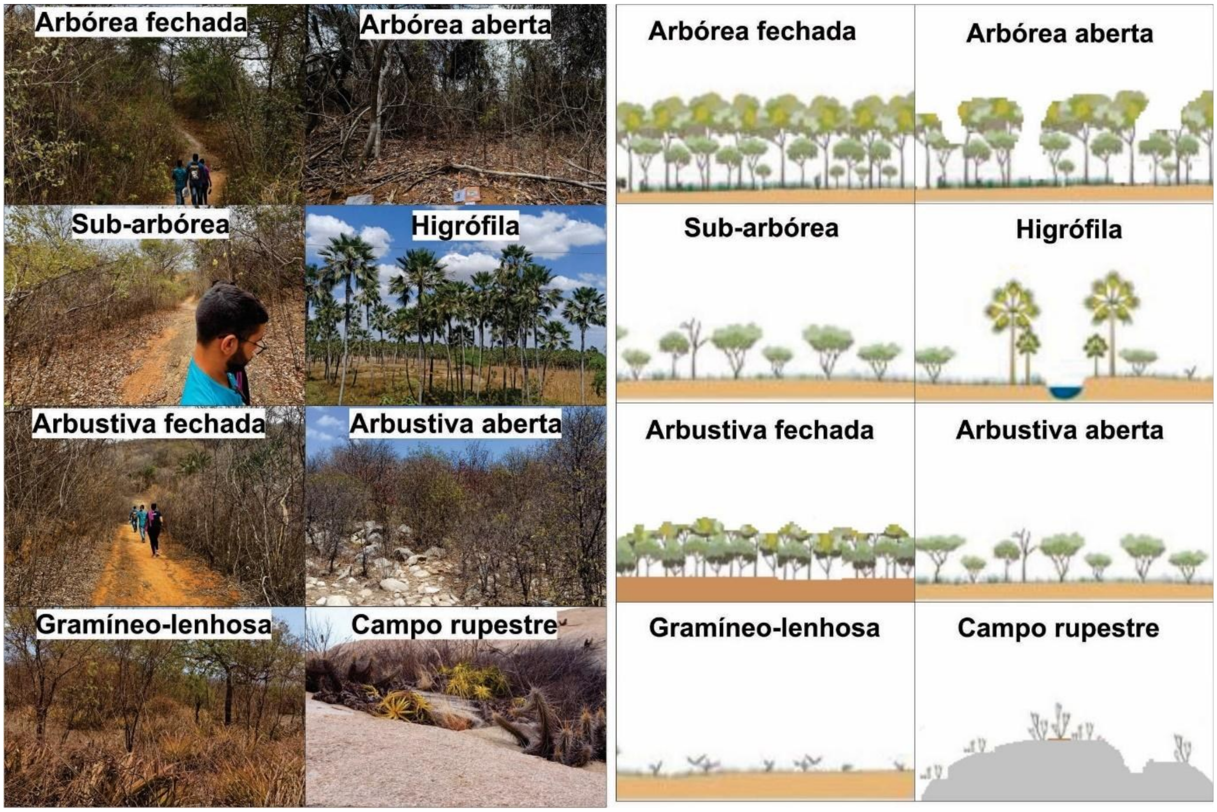


Figure 4 – Classifications of Caatinga subgroups and associated formations.
Legend: Closed Arboreal Vegetation (Arbórea fechada), Open Arboreal Vegetation (Arbórea aberta), Sub-arboreal Vegetation (Sub-arbórea), Hygrophilous Vegetation (Higrófila), Closed Shrub Vegetation (Arbustiva fechada), Open Shrub Vegetation (Arbustiva aberta), Grassy-Woody Vegetation (Gramíneo-lenhosa) and Rocky Field Vegetation (Campo Rupestre).
Source: Authors (2025). Adaptations of schematic figures from Cavalcanti (2014).

The integrated analysis demonstrates that vegetation formations are distributed along a morphoedaphic gradient in which soil depth, topographic position, slope gradient, and water availability constitute structuring variables (Fig. 4). Transitions between formations may occur gradually along slopes; however, in sectors marked by abrupt lithological changes or by the presence of rock outcrops, clear discontinuities in vegetation physiognomy are observed.

In this context, arboreal formations (closed and open) are predominantly concentrated in areas with deeper and better-structured soils, particularly on the summit surface (SS) and on slope sectors (SL) with lower stoniness. The floristic survey confirmed the presence of typical arboreal Caatinga species such as *Myracrodruon urundeuva* Allemão (aroeira), *Aspidosperma pyrifolium* Mart. & Zucc (pereiro), *Amburana cearensis* (Allemão) A. C. Sm (cumaru), *Anadenanthera colubrina* (Vell.) Brenan (angico), and *Libidibia ferrea* (Mart. ex Tul.) L. P. Queiroz (jucá), indicating environments with greater root support capacity and relative geomorphological stability.

The expressive occurrence of *Syagrus cearensis* Noblick (coco-catolé) in different compartments (SL/SS) reveals the ecological plasticity of this palm and reinforces the influence of local edaphic conditions in shaping vegetation facies, as recognized by IBGE (2012). The marked presence of palms confers structural singularity to the landscape, particularly in sectors with greater accumulation of colluvial material.

On slopes, open arboreal and subarboreal vegetation is observed, associated with moderately shallow soils and greater exposure to erosive processes. In these areas, canopy density is lower, reflecting limitations imposed by slope gradient and reduced water retention. Species such as *Mimosa tenuiflora* (Willd.) Poir., *Piptadenia stipulacea* (Benth.) Ducke, and *Croton heliotropiifolius* Kunth demonstrate typical xerophytic adaptations to environments subjected to pronounced water stress.

Shrub and grassy-woody formations (Fig. 4) predominate in sectors with shallow soils, greater surface stoniness, and, in some cases, direct influence of the crystalline basement (e.g., *Croton jacobinensis* Baill., *Lippia grata* Schauer, and *Varronia dardani* [Taroda] J.S. Mill.). In these areas, the herbaceous layer assumes greater relative importance, whereas woody individuals occur sparsely or in isolated clusters. This configuration highlights edaphic limitation as a determining factor in vegetation structure, confirming the strong dependence between pedogenesis and phytophysiognomy.

Particular emphasis should be given to the rocky fields of Serra do Lima, developed over rock outcrops (RO), where only small pockets of extremely shallow soils occur (Fig. 5). In these compartments, vegetation presents high ecological specialization, with predominance of herbaceous–shrub species adapted to water scarcity and intense solar radiation. Bromeliads are abundant, especially *Encholirium spectabile* Mart. ex Schult. f. (macambira), as well as cacti such as *Pilocereus gounellei* F.A.C. Weber ex K. Schum. (xique-xique) and *Pilosocereus pachycladus* F. Ritter (facheiro), which stand out as some of the most characteristic elements of these environments. The dominance of these plant groups in RO reflects a set of morphophysiological adaptations to environmental stress, including succulent tissues, CAM metabolism, and shallow root systems efficient in capturing water derived from episodic rainfall events.

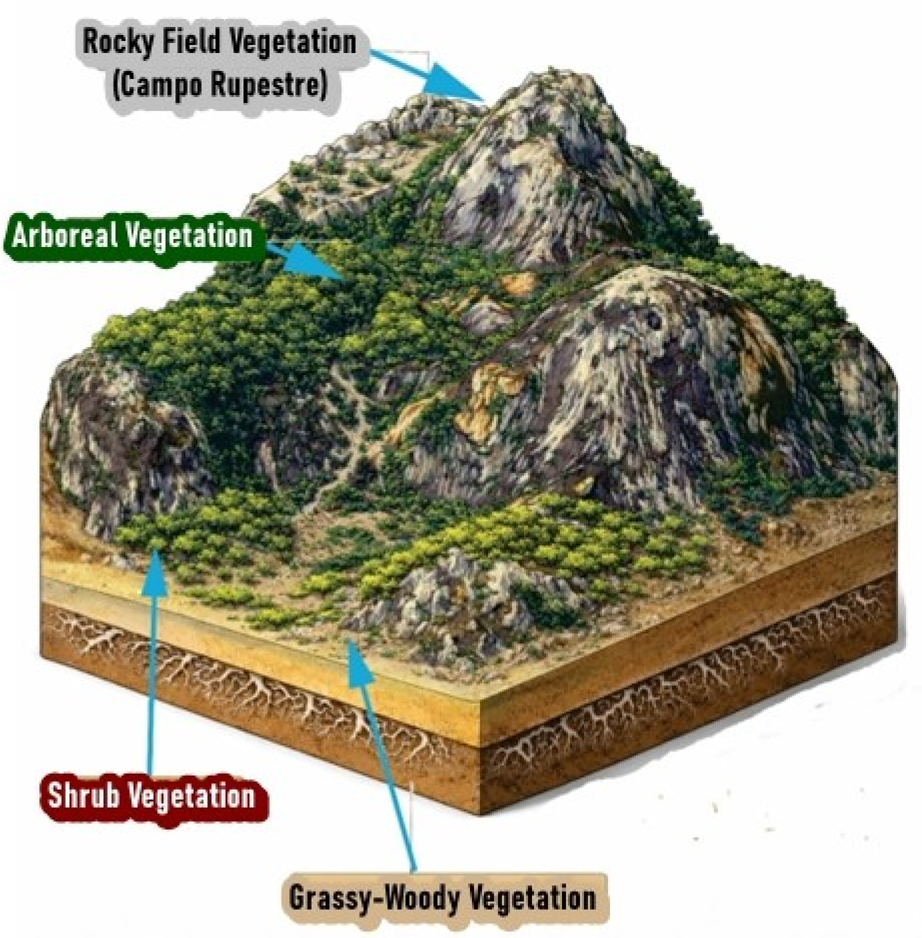


Figure 5 – Representation of Caatinga subgroups and associated formations in Serra do Lima, highlighting rocky fields in summit areas, such as the sector known as "Pelado", sectors with arboreal vegetation on elevated plateaus, shrub vegetation on slopes and foothills, and grassy-woody vegetation at the base.
Source: Authors (2026).

According to Borges Neto et al. (2025), inselbergs in the Brazilian semiarid region contain soil pockets (*pocket soils*) where geomorphological organization favors water retention, accumulation of fine sediments, and deposition of organic matter, forming sites with differentiated microenvironmental conditions relative to adjacent areas. These pockets present singular physical and chemical properties, transforming them into ecological refuges. Similarly, in Serra do Lima, cavities and discontinuity surfaces of the rocky substrate (e.g., gnammas, fissures, and fractures) also play an important role as ecological refuges, since the retention of moisture, sediments, and organic matter allows the formation of microhabitats favorable for the development of shrubs, bromeliads, cacti, grasses, and, in some cases, arboreal species under conditions of intense water and solar stress. Thus, soils in inselbergs play a strategic role in the migration and maintenance of plant species sensitive to water scarcity, including those typical of more humid biomes, contributing to the conservation of functional ecosystems within the Caatinga Domain (Borges Neto et al., 2025).

Field observations allowed the interpretations derived from laboratory analysis to be confronted with the real conditions of the landscape, making it possible to identify patterns in the phytophysiognomic distribution throughout the study area. In Serra do Lima, the results demonstrate that the spatial organization of vegetation is directly associated with relief compartmentalization, soil depth and properties, and hydrological dynamics, which play a determining role in defining phytophysiognomies. The integrated landscape analysis adopted therefore demonstrates that vegetation constitutes a direct expression of soil–relief interaction (Santos et al., 2023).

4. Conclusions

The integrated analysis of soil–relief–vegetation interactions in the Caatinga Domain demonstrates that the spatial organization of vegetation cover in the Brazilian semiarid region results from a multiscalar system of environmental controls. Although the semiarid climate establishes the regional macroecological framework, vegetation variability is strongly conditioned by local geoenvironmental factors such as topographic position, soil depth and fertility, lithology, and hydrological dynamics.

The terminological review revealed that the multiple denominations attributed to Caatinga vegetation reflect distinct theoretical and methodological frameworks. The consolidation of the term Steppe Savanna by IBGE (2012) contributed to national cartographic standardization but presents limitations by incorporating geomorphological and pedological controls only secondarily.

The geoenvironmental approach proved more effective in interpreting the heterogeneity observed in mountainous environments and along altitudinal gradients, revealing that different vegetation formations correspond to functional responses to the conditions of the physical substrate.

It is therefore concluded that understanding Caatinga vegetation requires moving beyond strictly physiognomic classifications, incorporating an integrated perspective that recognizes the structuring role of soils and relief in the spatial organization of vegetation formations. Such an approach expands the explanatory capacity of the patterns observed in the semiarid region. In addition to contributing to the theoretical and methodological advancement of the Geosciences, this perspective provides relevant technical foundations for territorial planning and the sustainable management of ecosystems.

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