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# *VEGETATION STRUCTURE AND ECOGEOGRAPHICAL CONTROLS IN MUD VOLCANO ECOSYSTEMS OF THE MUD VOLCANOES GROUP STATE NATURE RESERVE*

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## Abstract

This study provides a comprehensive analysis of vegetation structure and its ecogeographical controls within areas occupied by mud volcanoes included in the Mud Volcanoes Group State Nature Reserve. The research focuses on identifying the key environmental factors shaping vegetation distribution, including soil salinity, moisture availability, climatic conditions, geochemical processes, volcanic activity, and anthropogenic pressure.

Vegetation characteristics of mud volcano landscapes were examined through an integrated approach combining Sentinel-2 satellite imagery, the Normalized Difference Vegetation Index (NDVI), and relevant scientific literature. Plant species composition, spatial distribution patterns, and variations in vegetation density were analyzed across different landscape complexes within the reserve. Particular attention was given to comparing ecogeographical parameters influencing vegetation development in contrasting environmental settings.

Based on the obtained results, thematic maps, tables, and graphical materials were prepared to illustrate vegetation patterns and ecological differentiation across the study area. The findings highlight the strong dependence of vegetation cover on local environmental conditions and demonstrate the effectiveness of remote sensing data in assessing vegetation dynamics in extreme and fragile mud volcano ecosystems.

**Keywords:** *mud volcanoes; vegetation structure; NDVI; halophytic vegetation; ecogeographical factors; protected areas*

## 1. Introduction

Mud volcanoes represent distinctive geological formations formed by the extrusion of clay-rich material to the Earth's surface under the influence of water and gas pressure. When sufficient quantities of fluids and gases accumulate at depth, the clayey material becomes semi-fluid and migrates upward through fractures and fissures within the crust, eventually spreading across the surface [5]. The expelled material forms characteristic volcanic cones, flows, and breccia fields [2].

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Unlike magmatic volcanoes, mud volcanoes are not associated with high temperatures. The fluids discharged during eruptions are typically enriched with dissolved minerals but remain relatively cool, as their activity is driven primarily by gases generated during the decomposition of organic matter in deep sedimentary layers rather than magmatic heat sources [7]. This fundamental difference determines the physical and chemical properties of mud volcano environments and their ecological consequences.

Vegetation associated with extreme geological phenomena-such as geothermal fields, hot springs, solfataras, and mud volcanoes-provides valuable insights into plant adaptation, spatial organization, and ecosystem functioning under stressful environmental conditions. These environments serve as natural laboratories for studying vegetation dynamics, succession processes, and species resilience over time. However, despite growing interest in extreme habitats, vegetation on volcanic landforms, particularly mud volcanoes, remains comparatively understudied [4].

Vegetation constitutes a key component of natural landscape complexes, and its structure and spatial distribution are closely linked to ecogeographical factors. In mud volcano areas, vegetation development is strongly influenced by soil properties, degree of salinization, moisture availability, climatic conditions, and varying levels of anthropogenic impact. These factors interact to create highly heterogeneous environments where only specialized plant communities can persist.

The present study focuses on mud volcano areas located within the Mud Volcanoes Group State Nature Reserve, which encompasses territories in the Absheron, Shamakhi-Gobustan, and Lower Kura oil and gas regions. These areas are characterized by arid and semi-arid climatic conditions, saline soils, and active or dormant mud volcanic processes, making them particularly suitable for analyzing vegetation–environment relationships [3].

Plants function as important environmental indicators. The distribution patterns of adapted plant species provide valuable information about environmental conditions, while their individual stability and development reflect the degree of habitat suitability [8]. Vegetation dynamics therefore play a significant role in ensuring ecological balance and contribute to the principles of sustainable development in fragile ecosystems [9, 10].

By examining vegetation patterns within this protected area, the study aims to contribute to a deeper understanding of how extreme geological and ecological factors jointly shape plant distribution and structure in mud volcano ecosystems.

The selection of the Mud Volcanoes Group State Nature Reserve as the study area is justified by its exceptional concentration of terrestrial mud volcanoes and the presence of highly heterogeneous saline and semi-arid landscapes. Despite its ecological significance, detailed spatial assessments of vegetation structure using satellite-based indices remain limited. Therefore, this study aims to fill this gap by applying remote sensing techniques to evaluate vegetation–environment relationships in this protected volcanic ecosystem.

## 2. Materials and Methods

The ecogeographical analysis of vegetation within the Mud Volcanoes Group State Nature Reserve was conducted using an integrated methodological framework that combined remote sensing techniques, geographic information systems (GIS), cartographic materials, and existing scientific literature. This multidisciplinary approach enabled a detailed assessment of vegetation structure, spatial distribution, and environmental controls across the study area.

Sentinel-2 satellite imagery was employed as the primary data source for evaluating vegetation cover and condition. The Normalized Difference Vegetation Index (NDVI) was used as a key indicator to quantify vegetation density and assess plant health. NDVI values were calculated based on the reflectance characteristics of the red and near-infrared spectral bands of Sentinel-2 imagery. These data were obtained from the Copernicus Open Access Hub and processed using ArcGIS software to ensure accurate spatial analysis and visualization. Sentinel-2 Level-2A satellite imagery acquired on May 2024 during the peak spring vegetation period was used for NDVI analysis. The selected date corresponds to the seasonal maximum of ephemeral and halophytic vegetation development in arid and semi-arid environments of the Absheron Peninsula. Cloud cover was below 5%, ensuring high radiometric quality and reliability of vegetation assessment.Sentinel-2 multispectral imagery provides spatial resolutions of 10 m (Bands 2, 3, 4, and 8) and 20 m (Bands 5, 6, 7, 8A, 11, and 12). NDVI was calculated using Band 4 (Red, 10 m) and Band 8 (Near-Infrared, 10 m), allowing detailed detection of vegetation heterogeneity across volcanic surfaces and semi-desert landscapes.

Spatial analysis involved the classification of NDVI values to distinguish areas with absent, weak, moderate, and dense vegetation cover. The resulting NDVI-based maps allowed for the identification of vegetation patterns in relation to topography, soil characteristics, and mud volcanic landforms. Particular attention was given to volcanic cones, craters, breccia fields, and surrounding landscapes, where environmental stress factors are most pronounced.

In addition to satellite data, soil maps and vegetation maps of the reserve were analyzed to evaluate the influence of soil type, salinity, and moisture conditions on vegetation development. Information on anthropogenic impact—such as grazing intensity, proximity to settlements, and land-use practices—was also incorporated to assess human-induced pressures on plant communities.

The study further relied on published scientific sources, regional atlases, and thematic maps describing the geological, climatic, and ecological characteristics of the Absheron, Shamakhi–Gobustan, and Lower Kura regions. These materials provided essential background information for interpreting vegetation patterns and understanding their ecological context.

Field observations conducted within selected areas of the reserve were used to verify remote sensing results and to document dominant plant species and community types. Vegetation data obtained from field surveys were compared with NDVI values and cartographic materials to ensure consistency and reliability of the analysis.

By integrating satellite-based indicators, GIS techniques, literature data, and field observations, this methodological approach allowed for a comprehensive evaluation of vegetation structure and its ecogeographical determinants in mud volcano ecosystems.

The image processing workflow included the following stages: selection of cloud-free Sentinel-2 Level-2A imagery; verification of atmospheric correction (already applied in the Level-2A product); clipping of imagery to the boundaries of the Mud Volcanoes Group State Nature Reserve; NDVI calculation using the raster calculator tool in ArcGIS; classification of NDVI values into vegetation density classes; preparation of thematic maps and cartographic layouts.

## 3. Results and Discussion

Vegetation development on the surfaces of mud volcanoes represents a complex and long-term ecological process that involves both primary and secondary succession stages. Primary succession is characterized by the initial establishment of pioneer plant species on newly formed mud and breccia surfaces, whereas secondary succession occurs following repeated volcanic eruptions that periodically disrupt existing vegetation cover. These processes operate over both short and extended temporal scales and are strongly influenced by the frequency and intensity of volcanic activity.

Although the majority of mud volcano eruptions occur beneath the ocean floor, terrestrial mud volcanism is also relatively widespread and exerts a significant impact on surrounding landscapes and vegetation. Volcanic activity alters vegetation primarily through the deposition of mudflows, breccias, and fine-grained materials, as well as through the release of gases and saline fluids. These factors collectively limit plant establishment and contribute to the spatial heterogeneity of vegetation cover.

Phytocenotic analysis indicates that plant distribution on mud volcano surfaces is closely associated with the volume, direction, and extent of clayey mud emitted from volcanic vents. Areas subjected to intense mud accumulation are typically devoid of vegetation or exhibit extremely low species diversity. Consequently, vegetation patterns display a pronounced mosaic structure, with patches of barren surfaces interspersed with sparsely vegetated zones. The continuous movement and spreading of clay-rich mud prevent the formation of stable plant communities, restricting colonization primarily to halophytic species adapted to saline and poorly structured substrates.

The formation and distribution of vegetation in mud volcano areas are controlled by a combination of soil properties, climatic conditions, geochemical processes, volcanic activity, and anthropogenic influence. Soils in these environments are generally weakly developed and consist largely of unweathered primary mud deposits. They are characterized by high mineralization, elevated salinity levels, alkaline pH values (typically ranging from 8 to 9), low organic matter content, and poor structural development. These soil conditions differ markedly from adjacent semi-desert soils and impose severe physiological stress on plant species, allowing survival only of morphologically and physiologically specialized taxa.

Mud volcanoes within the study area are predominantly located in arid and semi-arid climatic zones, where annual precipitation is limited (approximately 200-400 mm) and temperature fluctuations are pronounced. During the summer months, intense solar radiation causes substantial soil heating, leading to increased evaporation rates and further accumulation of salts within the soil profile. These climatic factors exacerbate soil salinity and moisture deficits, thereby constraining vegetation growth.

Geochemical emissions associated with mud volcano activity also play a significant role in shaping vegetation patterns. Gases released during eruptions, such as hydrogen sulfide ($H_2S$), carbon dioxide ($CO_2$), and methane ($CH_4$), may exert toxic effects on plant tissues. At the same time, the presence of macroelements (Na, Mg, Ca, Fe) and trace elements (B, Mo, Sr) can influence nutrient availability for certain halophytic species. Mud volcano waters and breccias are often enriched with trace and potentially toxic elements, including Mo, As, Yb, B, Hg, Sr, Li, and Pb, frequently exceeding average crustal concentrations. The discharge of saline solutions to the surface results in the formation of highly saline lithogenic substrates, which favor the dominance of halophytic vegetation compared to surrounding non-volcanic areas [3].

Vegetation distribution and density are further affected by the temporal dynamics of mud volcano activity. During active eruptive phases, existing vegetation is destroyed, and the soil surface is covered by fresh mud deposits. Following periods of dormancy, vegetation recovery occurs gradually, beginning with ephemeral and halophytic species that are capable of rapid establishment under harsh conditions. With prolonged stability, shrubs and semi-shrubs may reappear, forming more structured plant communities.

Analysis of cartographic materials, literature sources, and field observations indicates that vegetation cover within the reserve is generally sparse and unevenly distributed. Dominant plant groups include xerophytes, halophytes, shrubs, semi-shrubs and ephemerals. Common halophytic species include *Atriplex tatarica*, *Halostachys caspica* and *Salsola dendroides* , while xerophytic elements are represented by *Artemisia fragrans* and *Astragalus aureus*. Ephemeral species such as *Alyssum desertorum* and various grasses (*Poaceae*) are widespread during favorable seasons, whereas shrubs and semi-shrubs, including *Tamarix ramosissima* and *Calligonum* spp., occur in relatively stable habitats.

Ephemeral plant communities occupying breccia surfaces are shown in. These communities play an important role in early-stage succession and contribute to short-term increases in vegetation cover following periods of volcanic inactivity.

**Fig. 1**. Distribution of Ephemeral Plant Communities on the Breccia Surface of Mud Volcanoes

The Mud Volcanoes Group State Nature Reserve is situated in the southeastern part of the Absheron Peninsula along the Caspian Sea coast. The area is characterized by volcanic landforms, saline soils, and arid climatic conditions. Despite the apparent severity of these environmental factors, the Absheron Peninsula supports considerable floristic diversity, with some locations hosting up to 10–12 plant species per square meter [11]. However, saline soils, limited precipitation, and strong winds restrict forest development, resulting in the dominance of semi-desert and halophytic vegetation types.

Coastal zones of the peninsula are characterized by saline vegetation dominated by halophytes such as *Salicornia europaea*, *Atriplex fomini*, *Nitraria schoberi* and *Suaeda confusa*. Moving inland from the shoreline, vegetation transitions through sandy and clayey zones to communities dominated by *Aster tripolium*, *Argusia sibirica*, *Anisantha rubens* and *Lactuca tatarica*. The distribution of *Limonium species* around the Shekikhan mud volcano.

**Fig. 2**. Distribution of *Limonium* sp. around the Shekikhan Mud Volcano

In northern coastal areas, species such as *Picris sirigosa*, *Astragalus bakuensis*, *Astragalus igniarius*, and *Cynodon dactylon* are common. In certain localities, this vegetation belt expands to include *Juncus litoralis*, *Phragmites australis*, and *Tamarix ramosissima.* At higher elevations, species composition changes, with *Ecballium elaterium* and *Capparis spinosa* becoming more prominent.

Several endemic and rare species occur within the study area, including *Calligonum bakuense*, which is confined to limited habitats. Extensive wormwood (*Artemisia spp.*) formations dominate large portions of the region, occasionally replaced by *Ephedra* spp. The floristic richness of areas such as the Gobu Valley and Qizilgaya is particularly notable during spring flowering periods [1, 10].

Distinct vegetation units were identified around individual mud volcanoes, reflecting differences in altitude, salinity, and substrate conditions. For example, the Pirakashkul mud volcano supports several salt-tolerant semi-desert communities, ranging from aggregated to fully developed associations [6]. Similarly, the Toragay mud volcano hosts diverse plant communities, including well-established salt-tolerant semi-desert associations dominated by *Salsola* and *Artemisia* spp.

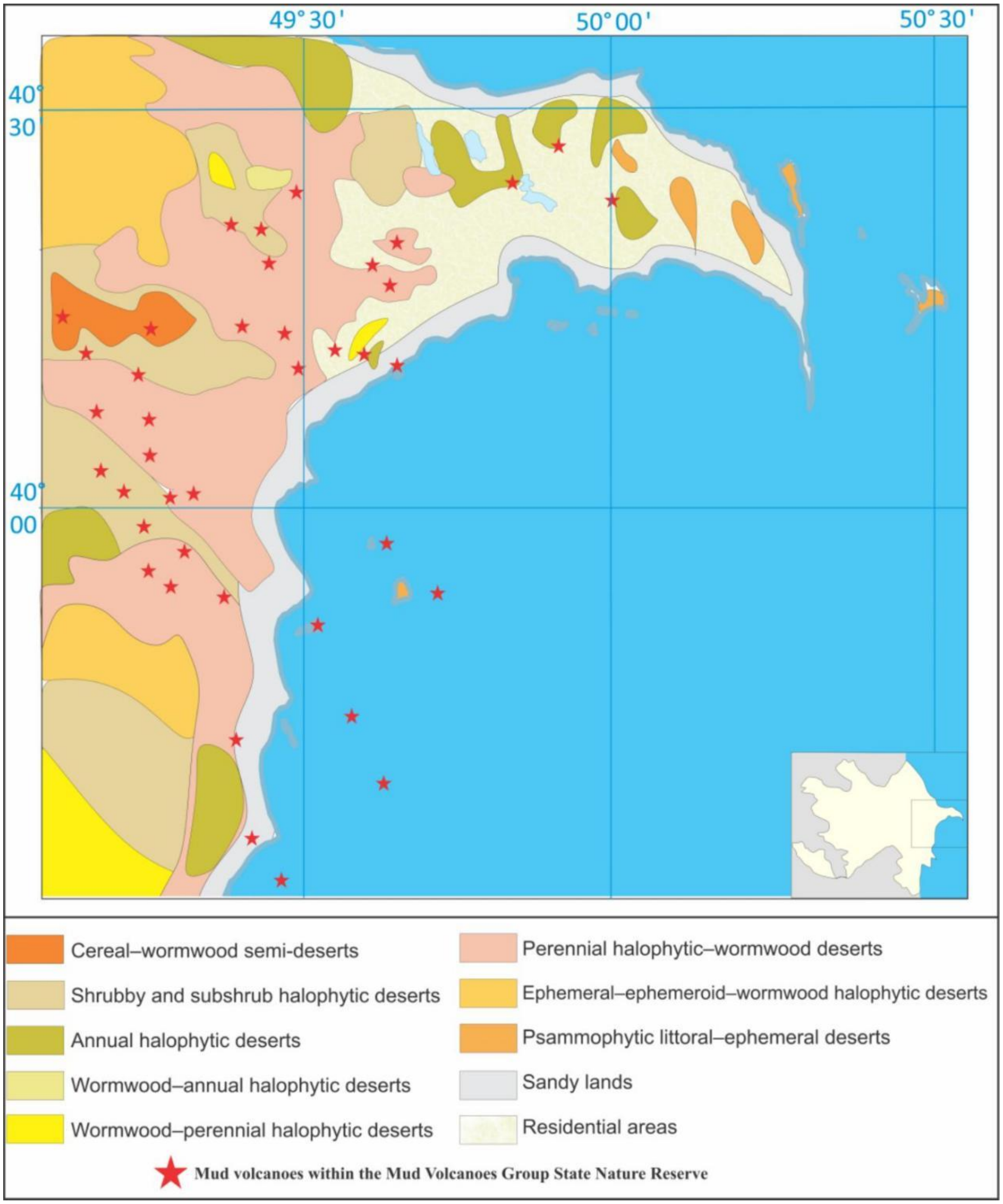


**Fig. 3**. Vegetation types of the Mud Volcanoes Group State Nature Reserve

NDVI analysis provided quantitative insight into vegetation condition across the reserve. Areas with NDVI values between 0.0 and 0.2 correspond to zones with absent or very weak vegetation, typically associated with active volcanic cones and crater zones. Moderate vegetation cover (NDVI 0.2–0.4) occurs in semi-desert and saline landscapes, while higher NDVI values (0.4–0.6) indicate relatively dense vegetation in more favorable environments. Vegetation patterns derived from NDVI data show a strong correlation with relief, soil type, and anthropogenic impact [12].

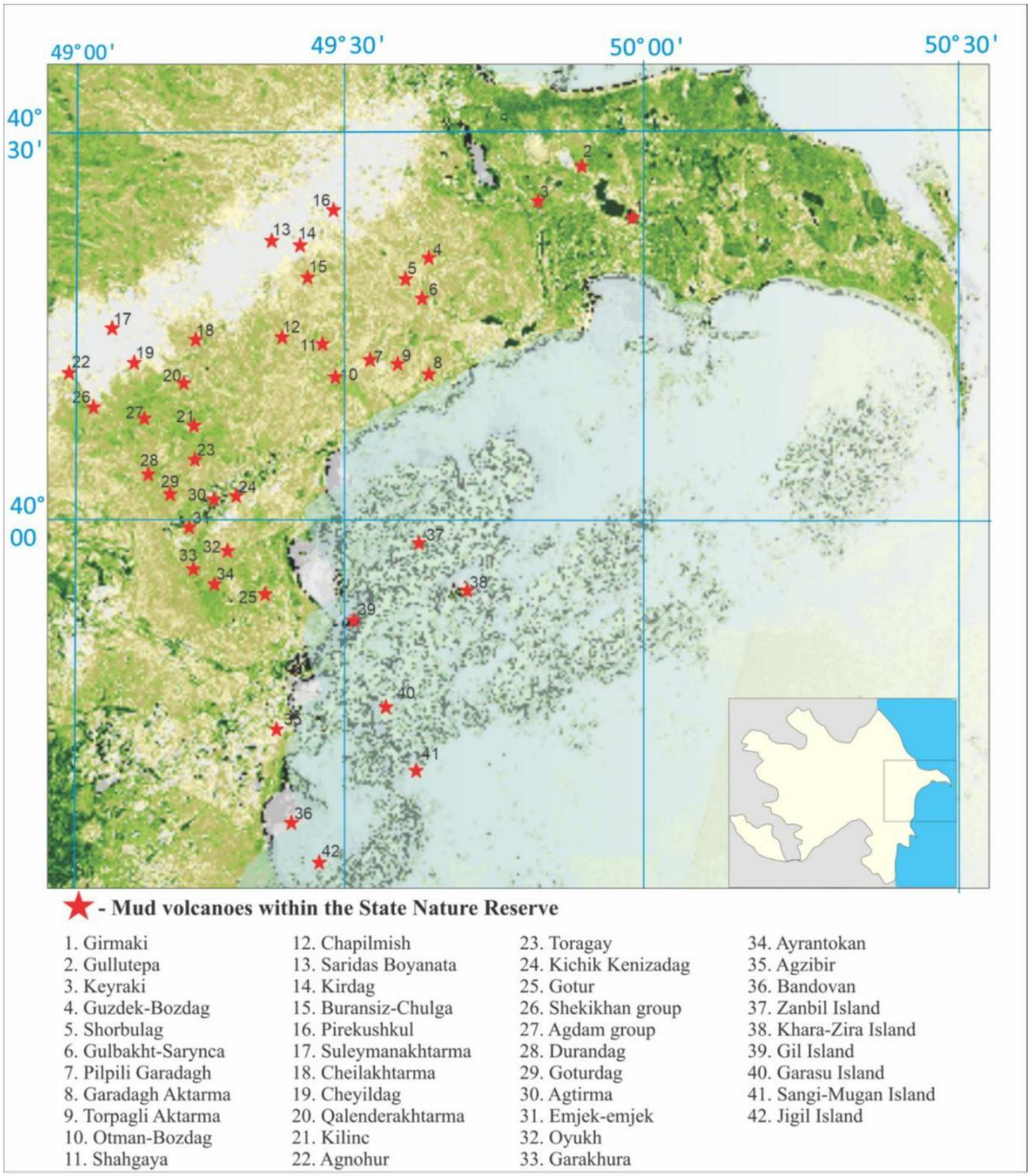


**Fig. 5**. NDVI analysis (Sentinel-2_L2A)
0.0-0.2 gray color; 0.2-0.4 brown color; 0.4-0.6 green color

Comparative assessment of landscape complexes within the Mud Volcanoes Group State Nature Reserve revealed a clear ecological differentiation associated with substrate stability, soil salinity, and disturbance intensity. Based on this assessment, an ecogeographical gradient model was developed to synthesize the relationships between environmental stress factors and vegetation development across volcanic and semi-desert landscapes. The model reflects a progressive transition from extreme, highly unstable volcanic surfaces to relatively stable steppe meadow ecosystems characterized by greater vegetation density and ecological resilience.

**Table 1.** Ecogeographical gradient model of vegetation development in mud volcano landscape complexes

| Landscape position (gradient) | Substrate stability | Salinity level | Mean NDVI class | Primary limiting factor | Ecological status |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Active mud cones and craters** | Very low | Very high | 0.0–0.1 (Absent) | Volcanic activity | Extreme stress zone |
| **Recent mudflow surfaces** | Low | High | 0.1–0.2 (Sparse) | Salinity, unstable substrate | High stress |
| **Salinized semi-desert plains** | Moderate | Moderate–High | 0.2–0.3 (Moderate) | Soil salinity | Transitional zone |
| **Dry shrublands** | Moderate–High | Moderate | 0.2–0.4 (Moderate–Relatively dense) | Moisture deficit | Semi-stable |
| **Steppe meadow complexes** | High | Low–Moderate | 0.3–0.5 (Relatively dense) | Anthropogenic pressure | Relatively stable |

The gradient model demonstrates that vegetation recovery and structural complexity increase proportionally with substrate stabilization and decreasing salinity levels. Active volcanic cones represent extreme ecological conditions where vegetation is absent due to continuous mud deposition and high mineralization. In contrast, steppe meadow complexes exhibit relatively dense vegetation cover despite anthropogenic influence, indicating improved soil structure and reduced geochemical stress.

This progressive ecological transition confirms that substrate stability and salinity are the primary determinants of vegetation distribution in mud volcano ecosystems, while climatic aridity and human disturbance act as modifying factors shaping community composition and density.

## 4. Conclusion

The ecogeographical assessment of vegetation within the Mud Volcanoes Group State Nature Reserve confirms that plant distribution and structural complexity are primarily controlled by substrate stability, soil salinity, and volcanic disturbance intensity. The developed ecogeographical gradient model clearly demonstrates a progressive ecological transition from extreme volcanic environments with absent vegetation to relatively stable steppe meadow ecosystems characterized by higher NDVI values and improved habitat conditions.

The results indicate that vegetation recovery in mud volcano landscapes follows a stability-driven trajectory, where decreasing geochemical stress and substrate consolidation facilitate the establishment of halophytic, xerophytic, and shrub communities. Although anthropogenic pressure influences species composition in more stable areas, natural geological processes remain the dominant drivers of vegetation differentiation within the reserve.

The integration of Sentinel-2 imagery and NDVI-based spatial analysis proved to be an effective approach for identifying ecological gradients, assessing vegetation density, and monitoring fragile mud volcano ecosystems. The proposed gradient framework provides a conceptual basis for long-term ecological monitoring, conservation planning, and sustainable management of protected volcanic landscapes under arid and semi-arid climatic conditions.

Overall, the study highlights the importance of integrating field observations, cartographic materials, and satellite-derived indicators to achieve a comprehensive understanding of vegetation–environment interactions in mud volcano landscapes. The findings provide a scientific basis for ecological monitoring, conservation planning, and sustainable management of vegetation within protected mud volcano areas.

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