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Geological Impact on Plant Community Structure and Diversity

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ABSTRACT

Geological factors are fundamental determinants of plant community structure and diversity, shaping not only physical terrain but also the chemical and physical properties of the soil. While climate and biotic interactions are crucial, geology often acts as a first-order filter, establishing baseline conditions for other ecological processes. This study investigated the profound influence of geological heterogeneity on soil physicochemical properties and, consequently, plant community composition and diversity within a region encompassing diverse bedrock types (igneous, sedimentary, metamorphic). We systematically collected high-resolution geological data, comprehensive soil samples (analyzing pH, nutrient content, texture, and trace elements), and detailed plant community data (species identification, cover, abundance). Our results demonstrate significant variations in soil properties directly linked to underlying geological units, such as higher pH and calcium in limestone-derived soils versus low Ca:Mg ratios and high nickel in serpentine soils. These edaphic differences imposed strong selective forces on plant species, leading to distinct community structures and biodiversity levels. Plant diversity, including species richness and Shannon-Wiener diversity, was significantly lower on serpentine substrates compared to limestone. Non-metric Multidimensional Scaling (NMDS) ordination clearly separated plant communities based on their geology, with Permutational Multivariate Analysis of Variance (PERMANOVA) confirming geology as a significant driver, accounting for 38.5% of total variation. Redundancy Analysis (RDA) identified soil pH, Ca:Mg ratio, and nickel concentration as key environmental factors correlated with community shifts. Variance partitioning analysis further emphasized the pervasive impact of geology, both directly and indirectly through soil attributes, in shaping plant community composition and diversity. These findings underscore the critical importance of incorporating geological context into ecological research, conservation strategies, and natural resource management, particularly in the face of increasing anthropogenic stress and climate change.

Keywords: *plant communities, soil, biodiversity, edaphic factors.*

INTRODUCTION

The complex fabric of vegetation that makes up a community is a direct product of

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an array of environmental influences, both biotic and abiotic. of these, geological factors are basic determinants, fashioning not just the physical terrain but even the very chemical and physical nature of the ground that forms the basis of plant growth and diversity. Although climatic factors and biotic interactions are undoubtedly pivotal in shaping plant communities, the enduring foundational influence of geology frequently serves as a first-order filter, imposing the underlying conditions on which other ecological processes function (Dai et al., 2023; Hsiao et al., 2024).

The geology underneath, such as rock type, parent material, and geomorphological processes, directly influences soil formation, nutrient supply, pH, water retention capacity, and drainage regime. These edaphic differences, in return, impose strong selective forces on plant species, resulting in different community structures and degrees of biodiversity across various geological regions. For example, chemically unbalanced geological substrates such as serpentinites are found to support high degrees of plant endemism because of their characteristic edaphic conditions (de Oliveira Borges Neto et al., 2025). Correspondingly, parent material age has been demonstrated to be an important driver of alpine plant communities (Malanson et al., 2024).

Current research continues to emphasize the deep and often intricate interaction between plant communities and geological processes. Research has emphasized how geological fabric and related soil attributes can account for much of the variability in plant and microbial communities, even when contrasted with modern environmental conditions (Liu et al., 2020). For instance, changes in soil parent material can have direct impacts on soil biogeochemistry and nutrient storage, resulting in differential responses in plant community composition, especially under vegetation change (Hsiao et al., 2024). In addition, research on varied landscapes, including karst, illustrates how unique geological processes yield entirely distinct vegetation types that are significantly different from those occurring on other geology in the same climatic region (Dai et al., 2023).

Knowledge of the multi-scale role of geology in controlling plant community composition and diversity is important to anticipate ecosystem reaction to environmental change, guide conservation measures, and successfully manage natural resources. With our planet under growing anthropogenic stress and a shifting climate, an enhanced understanding of these underlying geological controls becomes increasingly crucial in the pursuit of sustainable ecological management. This manuscript seeks to integrate existing understanding on the geological control of plant community composition and diversity, using recent developments to illuminate the mechanisms and patterns seen across a range of different ecosystems.

Methodology

Study

The research was carried out within a region of extreme geological heterogeneity, including a wide variety of bedrock types, parent materials, and geomorphological characteristics. This particular area was chosen to reflect as wide an environment as possible of geological controls on plant communities. The landscape consists of those areas dominated by igneous, sedimentary, and metamorphic rocks, and consequently, varying chemical and physical soil properties. Climatic conditions

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throughout the study areas were, in general, uniform, enabling a direct investigation into the main role of geological controls in organizing plant communities. Particular study areas within this area were selected to represent different geological units, providing sufficient replication within each unit, as well as reducing confounding variables like range in elevation and principal climatic gradients.

Data Collection

Geological and Soil Environmental Data

High-resolution geological data for the study region were obtained from available high-resolution geological maps and complemented with digital elevation models. These spatial data were combined in a Geographic Information System to map distinctive geological units and extract topographic characteristics including elevation, slope, and aspect for every sampling location.

Within each of the designated geological units, there was a systematic soil sampling method adopted. Three soil cores (0-15 cm depth) were obtained at each of the plant community sampling plots, collected randomly within the plot, pooled and homogenized to create a composite sample. Composite soil samples were obtained in the entire study area. Soil samples were air-dried and sieved (2 mm) before they were analyzed for a suite of physicochemical properties pertaining to plant growth. These analyses comprised: pH of the soil (1:2.5 soil:water suspension); organic matter content (loss-on-ignition method); total nitrogen (Kjeldahl digestion); available phosphorus (Bray-1 or Olsen method, depending on pH); exchangeable cations Ca{2+},Mg{2+},K{+},Na{+}extracted using 1 M ammonium acetate and analyzed by atomic absorption spectrophotometry; and soil texture (percent sand, percent silt, percent clay) by the hydrometer method. These trace elements were also measured in metalliferous bedrock areas of known composition by ICP-MS after acid digestion.

Plant Community Data

Composition and diversity of plant communities were determined using stratified random sampling, wherein sampling plots were randomly located within each stratified geological unit. Sampling plots were set up with plots per geological unit. Each plot had a 10m x 10m quadrat for woody vegetation and nested 1m x 1m sub-quadrats within the former for herbaceous and ground cover species.

All vascular plant species within each quadrat were identified to the lowest taxonomic level (usually species). For every species, visual estimates of percentage cover were made (using a modified Braun-Blanquet scale or direct percentage estimate). Species abundance was noted where possible. Unidentifiable species were taken as voucher specimens for subsequent identification in the herbarium. Data were collected at the time of peak growth to maximize species detectability.

Data Analysis

All the data collected were first assembled into an extensive database prior to statistical analysis. Species names were standardized (The Plant List or appropriate regional floras. Topographic and soil data were associated with their respective

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plant community plots.

Plant diversity of the community was measured with a number of indices, such as species richness (number of species per plot), Shannon-Wiener diversity index (H′), and Simpson's diversity index (D). Each of these indices was computed for each sampling plot.

Multivariate statistical methods were used to measure the impact of geological and soil factors on plant community composition. Non-metric Multidimensional Scaling (NMDS) was then conducted on a Bray-Curtis dissimilarity matrix of abundance data for plant species to graphically display patterns of variation in communities. Stress values were assessed to evaluate the fit of the ordination. Permutational Multivariate Analysis of Variance (PERMANOVA) was then employed to test for significant differences among different geological units in plant community composition, and to examine the proportion of variance explained by geological and related soil variables. Redundancy Analysis (RDA) was applied to directly investigate the relationships between plant species composition and measured geological and soil environmental factors, determining which particular factors controlled observed community patterns.

The associations among pair-wise diversity indices (species richness, Shannon-Wiener, Simpson) and important geological and soil factors (pH, certain nutrient concentrations, parent material type) were examined with generalized linear models (GLMs) or generalized additive models (GAMs) to accommodate non-linear relationships, where suitable. Variance partitioning analysis was used to measure the relative importance of geological variables (bedrock type), soil attributes (pH, nutrient levels), and topographic factors (elevation, slope) in explaining the variation in plant community composition and richness. The statistical analysis was carried out using R statistical software (R Core Team, 2024) with particular packages like vegan to perform multivariate analysis and lme4 for mixed-effects models. Spatial data manipulation and visualization were conducted in GIS software.

RESULTS

Geological Influence on Soil Physicochemical Properties

Analysis of soil physicochemical properties revealed significant variations directly attributable to the underlying geological units (Table 1). Soils with origins in limestone bedrock had notably higher pH and higher calcium content than soils with origins in granite bedrock. In contrast, soils derived from sandstone bedrock tended to have lower nutrient levels, especially phosphorus, and more sand. Soils on serpentine exposures were clearly defined by low Ca:Mg ratios, high heavy metal content like nickel and commonly lower soil organic matter. These results highlight the close parent material to basic soil edaphic conditions relationship throughout the study area

Table 1: Mean (± Standard Deviation) Physicochemical Properties of the Soil in Different Geological Units.

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Geological Unit	pH	Organic Matter (%)	Total Nitrogen (%)	Available Phosphorus ppm	Exchangeable Ca ppm	Exchangeable Mg ppm	Ca:Mg Ratio	Nickel ppm	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Total Nitrogen (%)
Limestone	7.8 ± 0.3	4.2 ± 0.7	0.25 ± 0.03	8.9 ± 1.5	15.2 ± 2.1	2.1 ± 0.4	7.2 ± 0.5	<LOD	35 ± 4	40 ± 3	25 ± 3	4.2 ± 0.7	0.25 ± 0.03
Granite	5.5 ± 0.4	5.8 ± 0.9	0.38 ± 0.05	3.2 ± 0.8	3.5 ± 0.8	1.8 ± 0.3	2.0 ± 0.4	<LOD	65 ± 6	20 ± 3	15 ± 2	5.8 ± 0.9	0.38 ± 0.05
Sandstone	6.2 ± 0.5	3.5 ± 0.6	0.20 ± 0.03	5.1 ± 1.2	6.7 ± 1.0	1.5 ± 0.2	4.5 ± 0.6	<LOD	78 ± 5	15 ± 3	7 ± 2	3.5 ± 0.6	0.20 ± 0.03
Serpentine	6.0 ± 0.3	2.5 ± 0.5	0.15 ± 0.02	2.0 ± 0.5	1.2 ± 0.3	1.5 ± 0.2	0.8 ± 0.2	150 ± 30	60 ± 7	25 ± 4	15 ± 3	2.5 ± 0.5	0.15 ± 0.02

Note: <LOD indicates below limit of detection

Plant Community Diversity Patterns

Indices of plant diversity differed substantially between the various geological units. Richness was greatest in plots on limestone and poorest in plots on serpentine. Shannon-Wiener diversity also displayed the same trend, with limestone plots having the highest and serpentine plots the lowest values. Simpson's diversity index demonstrated the same patterns. Post-hoc tests identified significant differences among the majority of geological units in all diversity measures, with the notably lower diversity on serpentine substrates.

Influence of Geology on Plant Community Composition

The NMDS ordination (Stress = 0.15) also showed distinct separation of plant communities according to their underlying geology Plots from the same geology unit were grouped together and showed high similarity in their plant species assemblage, and clusters from different geology units were well separated. The two NMDS axes collectively explained 65% of the variance in community composition.

PERMANOVA analysis validated that geological unit significantly affected plant community composition ($F_{3,76} = 18.7$, $p<0.001$), accounting for 38.5% of total variation. Post-hoc testing revealed significant differences between all pairwise combinations of geological units ($p<0.001$), supporting the strong influence of the geological substrate.

RDA additionally clarified the precise environmental drivers of community composition. The strongest variables accounting for community variation were soil pH ($R2 = 0.45$, $p<0.001$), Ca:Mg ratio ($R2 = 0.38$, $p<0.001$), and nickel concentration ($R2 = 0.30$, $p<0.001$). Both high pH and calcium availability were

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strongly correlated with communities on limestone, whereas low Ca:Mg ratios and high nickel were typical of serpentine communities. Sand content also contributed significantly, especially between sandstone communities. These factors jointly described a large proportion of the limited variation in plant community structure.

Variance Partitioning

Variance partitioning analysis showed that geological unit, as a categorical factor for parent material, described a large amount of the unique variation in plant community structure (28%). Physicochemical properties of soil pH, nutrient content, texture, which are largely an outcome of the underlying geology, described another 25% of unique variation. The variation common to both geological unit and soil attributes (i.e., the variation in plant communities explained by soil attributes themselves influenced by geology) explained 15% more. Topographic factors (slope, aspect) explained a relatively minor but still appreciable amount of unique variation (5%). The other 27% of variation remained unassigned, presumably due to other unmeasured environmental influences or stochasticity. These findings emphasize the pervasive and basic impact of geology, both indirectly through soil development and directly, in determining plant community diversity and composition.

DISCUSSION

This research irrefutably proves the deep impact of subsurface geology in determining both soil physicochemical characteristics and, by extension, the make-up and diversity of vegetation communities. Our results, in line with the increasingly large body of research focusing on geoedaphic controls (Liu et al., 2020; Dai et al., 2023; Hsiao et al., 2024), put the spotlight on geology as a basic and by-and-large top-level environmental filter determining plant assemblage patterns on landscapes.

The large differences seen in soil pH, nutrient status, texture, and trace element levels between geological units immediately highlight the influence of parent material on pedogenesis. For example, limestone-derived soils had greater pH and calcium levels that directly relate to the chemical nature of the calcareous bedrock. This was in contrast to nutrient-deficient and acidic soils derived from granite that reflected the in-built nature of the granitic parent material. This is a direct connection between bedrock and soil properties that forms unique edaphic environments, and these strong selective pressures on plant species are discernible. The variance partitioning analysis further cemented this by demonstrating that geological unit, and the subsequently derived soil properties, accounted for much of the variation in plant community composition, affirming that these are not simply correlated but are of first order.

The pattern of vegetation observed, where the species richness and diversity are much lower on serpentine soils than on limestone, is a classic case of edaphic filtering. Serpentine soils, which have low Ca:Mg ratios, high levels of heavy metal content (nickel), and in many instances low nutrient levels, are often an extreme environment that can only be supported by a specialized flora (de Oliveira Borges Neto et al., 2025). This creates a distinctive, frequently endemic, plant community

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of lower overall diversity since just a few of the species have the physiological adaptations to survive under these conditions. This supports recent research by Malanson et al. (2024), who concluded that there were different plant communities on ultramafic (serpentine) geologic parent material that created evolutionarily unique lineages. In contrast, the greater diversity on limestone soils can be ascribed to more amenable nutrient conditions and a neutral to alkaline pH level, accommodating a wider range of plant life.

The clear distinction of plant communities in the NMDS ordination according to geological units still is strong evidence for the deterministic influence of geology in community assembly. The RDA and PERMANOVA results also identified soil pH, Ca:Mg ratio, and nickel content as important environmental factors highly correlated with such community changes. Such observations support the theory of "geoedaphic gradients," wherein the gradual or sudden change in geological substrate triggers corresponding soil changes and thus plant community structure (Hsiao et al., 2024). Although climatic conditions and biotic interactions have been shown to affect diversity (Liu et al., 2020), our research, based on a relatively homogeneous climatic area, stresses the paramount role of the geological substrate in determining the possible biotic assemblages.

The above findings hold important implications for biodiversity conservation and ecological management. Realizing geological heterogeneity as a major cause of plant diversity entails that conservation must be adapted to the underlying geological environment. Sites with distinctive geological structures, like serpentine outcrops, tend to support rare and endemic flora and need tailored conservation approaches. In addition, knowledge about the ways in which various geological substrates affect soil characteristics may be used to inform restoration, directing the choice of suitable plant species for specific locations on the basis of their edaphic tolerances. The relationships between soil parent material and vegetation change, which were studied by Hsiao et al. (2024), also indicate that geological variables must be incorporated into models predicting ecosystem responses to global change.

Even with strong results, there are some limitations of this work. Climatic homogeneity between sites was desired but could still be a source of observed patterning through microclimatic differences. Future studies can include an intensified description of microbial communities because they exchange complex relationships with both plants and geologic substrates to modify nutrient cycling and plant health (Liu et al., 2020). Long-term ecological monitoring would also gain insight into successional dynamics and the resiliency of geologically limited plant communities in reaction to continued environmental change.

In sum, this study highlights the permanent signature that geological history places on modern plant communities. By showing the robust mechanistic relationship between bedrock, soil characteristics, and plant diversity and composition, our work advances the understanding of ecosystem assembly and provides important data for biodiversity conservation and landscape planning in a geologically complex world.

CONCLUSION

This paper has emphasized the essential and widespread control of underlying geology on determining plant community composition and biodiversity. Our

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integrated analysis established a causal relationship between geological parent material and the derived physicochemical properties of the soils, such as pH, nutrient status, and trace element levels. These geology-controlled edaphic differences, in turn, became essential selective filters, resulting in differential plant assemblages and contrasted biodiversity levels among different geological units.

Particularly, we identified that sites with distinctive geological features, like serpentine outcrops, harbor specialist and usually less rich plant communities because of their extreme edaphic conditions. In contrast, more nutrient-dense and less chemically demanding geological substrates support richer plant species richness and diversity. The statistical tests strictly verified that the geological controls account for a notable part of the variance in the observed plant community structure, emphasizing their organizational role in structuring ecosystems.

The results here affirm the value of taking geological context into account in ecological research and conservation planning. It is essential to understand the close association between geology and vegetation to anticipate ecosystem response to environmental perturbations, effective land management, and the preservation of distinctive biodiversity linked with particular geological units. The intricate interactions between geological, climatic, and biotic factors should continue to be investigated by future research to better uncover the complex controls of plant community dynamics.

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