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The Role of Geodiversity in Geoconservation Actions: An Integrated Framework

Eva Pescatore, Mario Bentivenga and Salvatore Ivo Giano *

Department of Basic and Applied Sciences, University of Basilicata, Via dell'Ateneo Lucano 10, I-85100 Potenza, Italy; eva.pescatore@alice.it (E.P.); mario.bentivenga@unibas.it (M.B.)
* Correspondence: ivo.giano@unibas.it

Abstract

Geodiversity represents a cornerstone concept at the intersection of geological, environmental, and biological sciences. As an abiotic equivalent of biodiversity, it encompasses the natural variety of geological, geomorphological, hydrological, and pedological features, as well as their assemblies, structures, systems, and functional processes. Its ecological significance is clear: geodiversity serves as the fundamental physical scaffold underpinning ecosystems, driving the complex, non-linear relationships that sustain biotic communities and regulate ecosystem services. In recent years, a growing number of studies have focused on refining the conceptualization of geodiversity and developing quantitative and qualitative frameworks for thematic mapping across multiple spatial scales—from local landforms to regional landscapes. However, translating these cartographic and spatial assessments into actionable conservation measures remains a critical challenge. Rigorous characterization of geodiversity is an indispensable prerequisite for geoconservation, as it provides the baseline evidence needed to identify abiotic vulnerability, establish protection priorities, and guide sustainable territorial planning. This paper presents a theoretical framework for classifying geodiversity, specifically structured in relation to target geoconservation actions. By categorizing abiotic elements through operational steps, this study provides a systematic decision-support tool that aligns diverse geodiversity components and vulnerability levels with specifically tailored conservation, restoration, and management actions.

Keywords: geodiversity; geoconservation framework; biodiversity–geodiversity interface; action-oriented framework

1. Introduction

Geodiversity is a descriptive term that has evolved over the past three decades from localized Australian nature conservation initiatives [1–3] into a comprehensive framework for environmental management [4–8]. Geodiversity shapes every aspect of our landscape, from rocks to building stones, and supports habitat biodiversity and the number of species associated with them. These are greater in areas where there is greater abiotic diversity, represented by a more or less articulated topography, the presence of morpho-biologic corridors, various soil and rock types, and the types of active or ancient geomorphological processes, which ensure and maintain vital ecosystems, as they support the diversity and variability of habitats on different temporal and spatial scales. The term emerged as scientists sought to address a major imbalance in nature conservation, which had historically prioritized living organisms while overlooking the abiotic physical world. Early foundational papers by Sharples [1,2,9] introduced the concept and defined it as "*the diversity of*

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earth features and systems", stressing that abiotic conservation must encompass active environmental processes—such as hydrological, geomorphological, and soil dynamics—rather than merely static geological monuments. Concurrently, Semeniuk [10] articulated the direct linkage between physical substrate variation and ecological patterning. During the first decade of the 2000s, a large number of papers were dedicated to geodiversity; among them, the papers listed below were chosen as representative of specific issues. Stanley [11] emphasized its connection to culture and ecosystem health, while Nieto [12] adapted the definition for educational and territorial planning frameworks in Southern Europe.

Afterwards, geodiversity shifted from a regional conservation concept to an internationally standardized academic discipline. Gray [13] provided one of the most widely cited definitions of geodiversity—conceptualized as the natural range of geological, geomorphological, and soil features, including their assemblages, relationships, and processes. Adopted by UNESCO [14], this formulation has strongly driven international geoscience and conservation initiatives. During the same period, Zwoliński [15] formally introduced the term into geomorphological literature through the Encyclopedia of Geomorphology [16]. Brocx and Semeniuk [4] proposed a comprehensive geoconservation methodology, establishing key terminology, assessment scales, and classification protocols across different landscape levels. Serrano and Ruiz-Flaño [17] established a comprehensive theoretical framework defining geodiversity as the variability of abiotic nature across physical processes, land surfaces, and oceans, while introducing a foundational four-tier hierarchy of abiotic diversity—spanning from simple particles and elements to places and complex landscapes.

As emphasized by Panizza [18], the geodiversity assessment cannot be reduced to the numerical richness of abiotic features; its interpretation depends on the characteristics, relationships, spatial organization, scale, and purpose of the assessment. Additionally, the author introduced the concept of morphodiversity, defined as "the critical and specific assessment of the geomorphological features of a territory". This assessment involves comparing these features both extrinsically and intrinsically, while considering the scale of investigation, the purpose of the research, and the level of scientific quality.

In a study on the geodiversity of landforms in the Polish Carpathians, aimed at providing a tool for sustainable tourism planning and identifying mountain areas requiring protection, Zwoliński [19] proposed a GIS-based method to measure and map geodiversity by analyzing key parameters, including relief energy, fragmentation, and the state of natural conservation. The study particularly emphasized the classification and categorization of landforms based on their relief energy, morphological type (ranging from high-mountain reliefs shaped by glacial and periglacial processes to flat valley floors), and conservation status (natural versus anthropogenic).

During the second decade of the 2000s, the scientific community increasingly focused on demonstrating the functional dependencies between abiotic and biotic nature, and on procedures for geodiversity quantification. Quantitative assessments by Parks and Mulligan [20] empirically linked abiotic diversity to broad-scale biodiversity patterns. ProGEO [21] published policy protocols for sustainable site management and specimen collecting. Building upon his foundational framework [13], Gray [5] expanded and integrated the definition of geodiversity, providing the comprehensive standard widely used today: "*Geodiversity is the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (landforms, topography, physical processes), soil and hydrological features. It includes their assemblages, structures, systems and contributions to landscapes*". Through this evolution, the updated definition: (i) explicitly incorporates hydrological features alongside soil and geological elements; (ii) highlights topography and landscape contributions, linking abiotic nature directly to spatial planning; and (iii) emphasizes structures and systems to capture active physical processes rather than static features. In the same period, Gray et al. [6] and

Gordon and Barron [22] aligned geodiversity with the ecosystem approach and natural capital, positioning physical landscapes as critical providers of geosystem services such as hazard regulation, carbon storage, and nutrient cycling. Semeniuk and Cresswell [23] proposed a scalar framework that links abiotic features directly to environmental selection and diversity, aiming to enhance the characterization of geodiversity from local to regional levels. Despite growing empirical evidence of a positive correlation between geodiversity and biodiversity, scientific progress and practical nature conservation face notable challenges due to variability in terminology [24]. Moreover, traditional frameworks frequently lack a straightforward, operational classification suitable for land management, spatial planning, and urban contexts where anthropogenic landforms play a crucial conservation role, as pointed out by Bradbury [25], who proposed a system based on scale and the physicochemical conditions that influence the formation of various aspects of geodiversity. The author established six classes, further divided into twenty-five themes, then categorized into 81 types, and ultimately into distinct elements. This study highlights the importance of separating management criteria and anthropogenic threats from the objective classification of geodiversity. This paradigm culminated in the framework advocated by Hjort et al. [26], which argued that protecting physical habitat diversity ensures long-term ecological resilience under climate change—a principle subsequently integrated into protected area policies by Crofts [27]. Zwoliński et al. [28] reviewed the methodologies for assessing and mapping geodiversity published in previous years. The authors categorized these approaches based on their data sources, distinguishing between direct field-based techniques and indirect methods, such as GIS and remote sensing analyses. They also classified processing procedures into qualitative, quantitative, and hybrid frameworks. Among these, hybrid multi-criteria decision-making approaches, like the Analytic Hierarchy Process (AHP), were emphasized as the most effective, as supported by the case study of the Dębnica River basin. These methods combine expert domain knowledge with statistical modeling and geomorphometric parameters derived from Digital Elevation Models (DEMs). Brilha et al. [7] emphasized that, through both the qualitative and quantitative characterization of geodiversity and the integrated management of extractable (geoplanning) and non-extractable (geoconservation and geoheritage) resources, abiotic nature plays an essential role in achieving the Sustainable Development Goals of the UN 2030 Agenda. Several quantitative methods for geodiversity assessment have been proposed (e.g., refs. [17,29–33]), focused on specific geodiversity aspects. An interesting concept derived from biology (biodiversity hotspot [34,35]) is that of geodiversity hotspots, which is currently under active development [31,36–39].

In recent years, research has shifted toward resolving methodological inconsistencies and harmonizing global monitoring systems. Addressing concerns raised by Maliniemi et al. [40] regarding how ambiguous and conflicting definitions have hindered the integration of geodiversity into ecological models, Hjort et al. [41] proposed a unified taxonomy to standardize abiotic classifications, utilizing 'geofeatures' as key operational units to systematically bridge abiotic and biotic conservation frameworks. Building on this effort, Schrodt et al. [42] introduced a framework of Essential Geodiversity Variables (EGVs), bringing abiotic monitoring into direct alignment with Earth observation satellites and global biodiversity indicators to support integrated nature management.

In this broader conceptual framework, the "Conserving Nature's Stage" approach—developed primarily in a biological context—represents a conservation-planning framework that focuses on protecting the physical, abiotic environment (geodiversity) rather than tracking individual species. As originally highlighted by Hunter et al. [43], maintaining biological diversity is most effective when conservation efforts focus primarily on protecting diverse physical environments rather than temporary plant communities. Because these

physical environments serve as stable "arenas" of biological activity, long-term species survival relies on managing reserves around these physical templates, ensuring organisms have the necessary space to shift and adapt as environments change. This approach has further evolved over time (see, among others, refs. [44–46]) and has become deeply intertwined with the geological context [47–53]. Furthermore, significant methodological progress has been achieved in defining geodiversity concepts ([6,17] with reference therein) and developing quantitative geodiversity assessments, ranging from regional grid-based GIS modeling and index calculations [29,32,54–57] to rapid quantitative-qualitative evaluations and biodiversity-oriented investigations [58–60]. However, these quantitative indices are often intrinsically contingent upon specific environmental regimes, data availability, spatial resolution, and local morphodynamic processes. In contrast, the framework proposed here does not aim to quantify abiotic richness or rank site significance, but rather provides an expert-guided qualitative characterization specifically structured to guide technical-administrative decision-making and land-use policy integration.

In this context, the present study highlights the necessity of distinguishing among specific geodiversity types to better guide geoconservation actions. Accordingly, an integrated operational framework was proposed, categorizing abiotic components into distinct thematic classes to align targeted conservation, restoration, and management measures with site-specific vulnerabilities.

2. Materials and Methods

The methodological framework adopted in this study is designed to bridge the gap between theoretical geodiversity assessment and practical territorial management, providing a structured, replicable workflow.

In general, within geoconservation actions, the methodological process can be articulated through distinct operational phases. First, Geo-Environmental Characterization conducts a physical diagnosis of the territory, analyzing geological and geomorphological features while assessing intrinsic site vulnerability and exposure to natural or anthropogenic hazards. Next, GeoHeritage and Cultural Evaluation assesses scientific significance, rarity, educational potential, and cultural interconnections to provide a solid rationale for conservation interventions. Third, Regulatory and Administrative Alignment carries out a legal and institutional feasibility assessment, reviewing statutory protection regimes, spatial planning instruments, and governance frameworks to ensure full compliance. Fourth, Anthropogenic Pressure and Risk Assessment evaluates human disturbance, land-use changes, visitor carrying capacity, and resource exploitation risks to define targeted mitigation and restoration measures. Finally, Participatory Governance and Stakeholder Co-Design engages local authorities, communities, and scientific institutions throughout the planning cycle to co-design a sustainable management plan and foster local stewardship.

Note that the site selection and evaluation phases are intentionally omitted, as this paper does not deal with the quantitative assessment of a site's significance and importance, but rather with its characterization for planning geoconservation interventions, with particular regard to geodiversity. In these terms, a qualitative evaluation structured on a three-tier scale (low, medium, high) is adopted for the examples presented in the Section 4, where this aspect will be further clarified. More generally, this simplification should be understood as a synthetic expression of specific quantitative studies. Furthermore, this proposed framework is explicitly designed to be scale-independent and adaptable across diverse spatial contexts, varying territorial dimensions, and distinct protection regimes (ranging from strictly protected areas to unprotected municipal lands). Rather than establishing an absolute priority ranking or a quantitative significance score—where higher ratings imply greater conservation status or hierarchical value—the adopted three-tier ordinal scale

(1 = Low, 2 = Moderate, 3 = High) serves purely as a descriptive qualitative characterization. This classification reflects the presence and thematic representativeness of each geodiversity class within a given site setting.

From a communicative and governance perspective, adopting this simple three-tier system enhances cognitive accessibility for non-specialist stakeholders, municipal planners, and local decision-makers who may lack specialized geoscientific backgrounds. Providing a clear, non-hierarchical, and shared language enables technical and non-technical actors alike to interpret site-specific territorial complexity and seamlessly incorporate geodiversity criteria into administrative planning workflows.

To ensure the operational effectiveness of these phases, the proposed framework considers geodiversity as the expression of multiple components categorized across distinct functional groups and thematic classes. By systematically characterizing these geodiversity components, the model guides the selection of geoconservation actions tailored to local environmental dynamics. While the authors are fully aware of the inherent weaknesses of qualitative methods—specifically regarding potential subjectivity—this constraint also represents a key strength. Rooted in real scenarios, empirical observations, and direct field experience, this qualitative approach enables the development of tailored procedures that closely align with local conditions and respect the unique features of the territory. All figures and tables presented in this paper were developed by the authors, reflecting both direct research experience and the specific challenges brought to their attention by local territorial managers. The following sections present and detail these conceptual and methodological components.

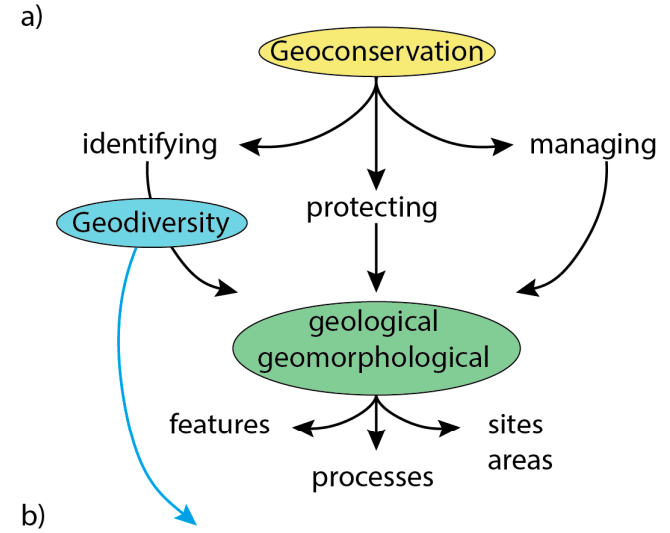
2.1. Geodiversity Classification Framework for Geoconservation Actions

According to Gray et al. [6], physical landscapes should be viewed as dynamic components of natural capital rather than static elements. They provide essential ecosystem and geosystem services to society, including the regulation of natural and human-induced hazards, carbon storage, and nutrient cycling. In this context, geoconservation operates across several fundamental levels. First, it involves the protection of natural heritage and its ecological integrity, where geodiversity plays a crucial role. The primary goal of geoconservation is to safeguard elements of abiotic nature that hold scientific, educational, or cultural value (geoheritage), ensuring that active environmental processes continue to function without undergoing irreversible degradation, whether from natural occurrences or human disturbances. Second, geoconservation aims to maintain the dynamic equilibrium of geosystem services, which may include efforts to restore or, where necessary, rehabilitate damaged functions. Third, as pointed out by Hjort et al. [26], conserving physical habitat diversity—a key aspect of geodiversity—is essential for sustaining biodiversity and providing long-term adaptive capacity under climate change. Finally, geoconservation serves as a fundamental pillar of sustainable development: by integrating the protection of abiotic heritage with land-use planning (geoplanning), geodiversity becomes an essential resource for achieving the UN 2030 Agenda Sustainable Development Goals, balancing environmental protection with sustainable economic growth [24].

According to UNESCO [61], geoconservation is defined as the practice of protecting and managing geological features and processes to ensure their preservation for future generations. By extension, it involves identifying, protecting, and managing geological and geomorphological features, processes, and sites (Figure 1a). Identification represents the first and essential phase of any geoconservation strategy. Without a systematic inventory and assessment phase, it is impossible to establish what deserves protection, what priority should be given, and what the most appropriate actions are. And this involves considering sites or areas designated for geoconservation measures not only based on their intrinsic or

extrinsic value, but also based on their physical characteristics and vulnerabilities [5,62–64] and the physical landscape in which they are included [65,66]. All factors have repercussions on management and protection methods. Several papers have been dedicated to the qualitative and quantitative assessment of geological heritage and geodiversity, both general and focused on individual examples (including [54] and references therein; refs. [67,68]). The scope of this study is intentionally qualitative, omitting a quantitative evaluation of geological heritage and geodiversity in favor of a descriptive approach.

a)



b)

Geodiversity	
Class	**Focus/Object of Analysis**
Areal/Spatial	Surface density and spatial heterogeneity of abiotic features per unit area
Geological	Bedrock composition, sedimentological facies, and stratigraphy. Geological assemblage (tectonic units) across multiple spatial scales (meso, macro). Geosites
Morphological	Landform assemblage across multiple spatial scales (micro, meso, macro). Geomorphosites
Palaeontological	Fossils, palaeoenvironmental records, geological times.
Mineralogical	Diversity of mineral species, crystal habits, and assemblages
Pedological	Soil variability, horizonation, and pedogenetic processes across spatial and temporal scales
Hydrological	Surface and subsurface water bodies, flow regimes, and hydrogeological interactions
Structural	Tectonic and deformational architecture across multiple spatial scales (micro, meso, macro)
Processual (Physical)	Active geomorphic processes, dynamic environmental transformations, hydrological processes.
Anthropogenic	Human-modified landforms, heritage quarries, and urban geodiversity

Figure 1. Conceptual workflow of geoconservation (**a**) and systematic classification of geodiversity components (**b**). (**a**) Operational diagram illustrating the primary pillars of geoconservation—identifying, protecting, and managing—focused on geological and geomorphological features, active processes, and designated sites/areas. (**b**) Detailed classification matrix outlining the main categories of geodiversity (from spatial and structural elements to dynamic and anthropogenic components) alongside their respective objects of analysis across multiple spatial–temporal scales.

To identify geodiversity, establishing clear definitions is crucial. Identification starts from the general concept of geodiversity expressed by Gray [5,13], within which the identification process selects elements with intrinsic scientific, educational, or touristic value, be they geosites [54,69] or geomorphosites [70]. To operationalize this identification process, geodiversity cannot be treated as a monolithic entity; rather, it requires a systematic classification into distinct analytical components. Classic definitions of geodiversity refer to the "natural range" of features and therefore exclude artificial/anthropogenic features. We agree that the foundational definition is strictly tied to natural conditions. However, with the evolution of modern geoconservation, urban geomorphology, and environmental management, contemporary landscape practice requires recognizing that human activities have profoundly modified physical substrates (e.g., historic quarries, artificial cut-slopes, and urban landforms) and integrating them into conservation frameworks. To clearly address this, Figure 1b distinguishes the classes related to the natural range (highlighted in green), which partially overlap with those proposed by Hjort et al. [41], from the one related to human action on the landscape (highlighted in red). This addition does not alter the core "natural" definition of geodiversity; rather, it introduces an operational "anthropogenic" class to account for human-landforms and urban/rural geodiversity as vital components of modern abiotic heritage in human-impacted contexts. Specifically, this anthropogenic category refers to the human modification of pre-existing geological and geomorphological elements, as well as urban geological heritage. Categorizing geodiversity into specific classes—ranging from Areal/Spatial heterogeneity to intrinsic Geological, Morphological, Structural, Pedological, and Hydrological architectures, as well as Palaeontological and Mineralogical records—allows for a more rigorous evaluation of the physical landscape across different scales. Furthermore, isolating active Processual (Physical) dynamics provides a comprehensive framework to assess both static elements and active environmental transformations. Finally, incorporating the Anthropogenic class acknowledges human-modified landforms and urban geodiversity as integral elements of modern abiotic heritage, thereby guiding targeted conservation, management, and valorization strategies.

As summarized in Table 1, this operational framework organizes geodiversity into five primary groups spanning ten thematic classes, linking specific field indicators to clear conservation goals.

At the broadest scale, the **Metric and Spatial group** (comprising the Areal/Spatial class) employs synthetic spatial metrics to quantify landscape patchiness, providing a broad-scale foundation to map overall geodiversity and delineate priority conservation hotspots.

The **Abiotic Components group**—such as Geological, Morphological, Pedological, and Hydrological—focuses on specific geological and physical architectures, soil profiles, hydrographic networks, and Earth history records across multiple scales. Note that the class Geology includes all sedimentary, igneous, and metamorphic components related to deposits, facies, and facies associations, whereas the class Morphology also encompasses characteristic volcanic, desert and other forms. These categories target fundamental habitat templates, stratigraphic sequences, pedological diversity, and water bodies that govern regional hydrogeological pathways, ecosystem functions, and slope stability. Similarly, Palaeontological and Mineralogical classes address fossil and crystal assemblages, prioritizing fragile localities and type sites to prevent over-collection and degradation.

The **Dynamic group** (including the Structural class) focuses on deformational architectures, fault networks, and regional stress regimes.

The **Processes group** (encompassing the Processual/Physical class) tracks active process-oriented environmental dynamics—such as erosion, pedogenesis, sediment transport, and active hydrological processes—ensuring the ongoing management and safety of evolving natural systems and rock slopes.

Table 1. Methodological classification matrix of geodiversity components, mapping abiotic classes against their focus of analysis, key indicators/geofeatures, and operational geoconservation relevance.

Geodiversity					
Group	**Class**	**Focus/Object of Analysis**	**Primary Indicators and Geofeatures**	**Geoconservation Relevance**	
Metric and Spatial	Areal/Spatial	Surface density and spatial heterogeneity of abiotic features per unit area	Synthetic geodiversity indices (km^{-2}), landscape patchiness	Identification of: geodiversity hotspots; priority conservation zones.	
Abiotic Components	Geological	Bedrock composition, sedimentological facies, and stratigraphy. Geological assemblage (tectonic units) across multiple spatial scales (meso, macro)	Stratigraphic sections, depositional sequences, petrographic variety	Preservation of Earth history features and palaeoenvironmental records	Scientific research and education
	Morphological	Landform assemblage across multiple spatial scales (micro, meso, macro)	Glacial, karst, fluvial, coastal landforms	Protection of physical habitat templates that may sustain biological diversity.	
	Palaeontological	Fossils, palaeoenvironmental records, geological times	Micro species, Macro species, type localities, rare species occurrences, species association	Site preservation and management, and protection against over-collection	
	Mineralogical	Diversity of mineral species, crystal habits, and assemblages	Type localities, rare species occurrences, ore body structures	Site preservation and management, and protection against over-collection	
	Pedological	Soil variability, horizonation, and pedogenetic processes across spatial and temporal scales	Soil profiles, paleosols, soil associations, organic matter content, soil texture/structure, pedodiversity indices	Protection of soil ecosystem functions, carbon storage, substrate support for biological habitats, and prevention of soil erosion/degradation	
	Hydrological	Surface and subsurface water bodies, flow regimes, and hydrogeological interactions	Rivers, lakes, aquifers, springs, wetlands, waterfalls, hydrographic networks, water quality/chemistry profiles	Management of freshwater resources, preservation of aquatic/riparian habitats, protection of hydrosites, and maintenance of natural hydrological cycles	
Dynamic	Structural	Tectonic and deformational architecture across multiple spatial scales (micro, meso, macro)	Fault zones, folds, joint networks, foliation patterns, microtectonics	Understanding deformational architectures, regional stress regimes, hydrogeological pathways, and rock slope stability	
Processes	Processual (Physical)	Active geomorphic processes, dynamic environmental transformations, hydrological processes.	Rates of erosion, sediment transport, soil formation (pedogenesis), karstification	Preservation or management of active environmental dynamics.	
Human	Anthropogenic	Human-modified landforms, heritage quarries, and urban geodiversity	Historical stone masonry, artificial cut slopes, industrial mining heritage	Cultural heritage preservation, urban geoheritage valuation, and brownfield restoration	

Finally, the **Human group** (incorporating the Anthropogenic class) integrates human-modified landforms, historical stone masonry, and brownfield sites into modern geodiversity management schemes.

Note that hydrological elements are explicitly integrated within the Abiotic Components. While water is inherently dynamic, stationary and structural water bodies—such as lakes, river networks, aquifers, springs, and wetlands—constitute fundamental physical features of geodiversity [5]. This classification aligns with recent integrative synthesis frameworks (e.g., refs. [71,72]), which recognize hydrology not merely as a fluid driver, but as a core structural domain of geodiversity. In this context, surface and underground

water systems provide essential physical and chemical templates, governing the hydro-pedological interactions and directly anchoring aquatic and terrestrial habitat structures. Conversely, the kinetic and functional aspects of water flows—such as discharge regimes, erosion rates, and karst dissolution—are included under the Processes group, ensuring a clear conceptual distinction between hydrological features as physical heritage and hydrological processes as drivers of landscape transformation. Similarly, a clear conceptual distinction is maintained regarding tectonic and structural features. Although structural discontinuities—such as fault lines, joint networks, and folding shapes—exert a strong primary control on surface landforms (Morphological class) and act as key drivers for active slope instability and weathering (Processual/Physical class), they are classified within the Structural category strictly based on their origin and tectonic geometry. This ensures that the primary geological framework is not confused with its surface morphodynamic expressions or active degradation processes. Collectively, across all ten classes, these targeted indicators not only safeguard Earth heritage but also serve as platforms to promote scientific research and educational initiatives. Each class represents not only a taxonomic label in itself, but also has a specific management impact on geoconservation actions (geoconservation relevance): from spatial metrics for planning, through the physical and stratigraphic protection of materials, up to the management of dynamic processes and the anthropized landscape. Overall, this classification framework is based on features and evolutionary dynamics currently observed and ongoing in the present context. Nevertheless, for specific classes, it can also accommodate the evaluation of non-active, fossilized, or relict expressions formed under previous climatic and environmental regimes.

As highlighted by Pescatore et al. [65], the approach to geoconservation varies significantly depending on the territorial context. In Natural and Protected Areas, the main goal is to preserve the dynamic balance between geological and biological systems, with human activities adapting to the needs of these natural systems. In Urban and Urbanized Areas, the priority shifts to ensuring the safety of the population, prompting adaptations in geoconservation actions. Lastly, in Anthropized Areas (i.e., natural environments that have been transformed by humans to meet their needs while still retaining certain natural elements), geoconservation focuses on maintaining, restoring, or creating geological diversity in human-altered landscapes (such as modified rivers or agricultural regions). Accordingly, geoconservation actions should not be seen merely as a passive attempt to protect geological heritage and geodiversity. Instead, they should be understood as an active, evolving process that requires the consideration of various factors from both geological and non-geological contexts.

In line with Pescatore et al. [65] and Bentivenga et al. [73], geoconservation actions can be broadly categorized as **conservative** (maintaining the status quo to physically preserve features and mitigate natural or anthropogenic impacts), **reconstructive** (focused on restoration and landscape recovery), or **creative** (designed to generate lost geological or geomorphological features). Recent discussions by Benado and Brilha [74] have focused specifically on restoration within geoconservation. They note that, unlike biodiversity or biological ecosystems, many geological elements have limited or no resilience and are virtually irreplaceable once destroyed. Consequently, traditional natural regeneration processes may not apply to geological heritage. Restoring this heritage, therefore, necessitates specific and extremely cautious strategies to prevent irreversible damage. Beyond active measures, geoconservation management must also contemplate scenarios where **non-action** constitutes the most effective strategy. In highly fragile or pristine environments, human interference—even when aimed at protection—can inadvertently disrupt fragile substrate balances or alter natural process-response systems.

Moreover, in sensitive geo-contexts, introducing access facilities risks inadvertently attracting unregulated 'wild' tourism, escalating pressures such as surface compaction, erosion acceleration, and overall disturbance to natural dynamics. Furthermore, such uncontrolled influxes often pose a real risk to local biodiversity—affecting both flora and fauna—as well as to the safety of visitors themselves. In such settings, adopting a passive management regime ensures that natural morphodynamic evolution remains unconstrained, serving as an untouched baseline for long-term ecological monitoring and geoheritage preservation. Far from representing neglect, this approach constitutes a deliberate strategy to prevent the ecological and morphological disruptions typically caused by artificial structures or unregulated access. This passive or hands-off regime could be particularly suited to restored landscape contexts. Following an initial active restoration phase, management should transition into a secondary 'renaturalization' stage, wherein the physical landscape is intentionally left unconstrained to regain its dynamic equilibrium naturally. A key example is river restoration: once structural measures—such as reintroducing meanders, wetlands, or morphological drops (such as small rapids and cascades)—are implemented, the river should, wherever possible, be allowed to evolve freely, and the system should be permitted to occupy its available spatial domain according to its intrinsic morphodynamics and natural evolutionary trajectories.

Geodiversity may play a crucial role in geoconservation efforts. However, geoconservation actions do not always directly influence geodiversity; instead, geodiversity can serve as a secondary objective or a "positive outcome" of such actions. Specifically, geoconservation measures targeted directly at safeguarding a sensitive geoheritage site (e.g., restricting access to a vulnerable palaeontological outcrop or restoring a dynamic geomorphosite) primarily protect specific abiotic assets. Nonetheless, by stabilizing the physical substrate, mitigating erosion, or restoring natural processual dynamics, these site-specific interventions may generate indirect benefits across the broader territorial matrix. To clarify how geodiversity can act as a secondary 'positive outcome' rather than the direct driver of geoconservation interventions, Table 2 outlines representative scenarios across different geoconservation strategies (conservative, reconstructive, creative, and passive). In these examples, geoconservation actions target specific geoheritage items or sites (e.g., a fossil locality, a degraded geomorphosite, or an industrial quarry) rather than geodiversity as a broad construct, ultimately yielding indirect positive effects on geodiversity at both the site and landscape scales.

Table 2. Operational typology of geoconservation actions—categorized into active (protective/preservative, reconstructive/restorative, and creative/anthropogenic interventions)—mapping representative site examples, primary objectives, key operational mechanisms, secondary ecological benefits, and positive outcomes on specific geodiversity classes and biodiversity ecosystem services.

	Geoconservation Action			
	Protective/ Preservative	**Reconstructive/ Restorative**	**Creative/ Regenerative**	**Non-Action/ Passive Management**
Example	Palaeontological and Mineralogical Sites	Geomorphosites (e.g., river meander or damaged dune system, karst areas).	Urban Geoheritage and Mining Sites.	Remote badlands, high-mountain cliffs, pristine geological outcrops, and inaccessible natural geosites.

Table 2. *Cont.*

			Geoconservation Action		
			Protective/ Preservative	**Reconstructive/ Restorative**	**Creative/ Regenerative**	**Non-Action/ Passive Management**
Direct Target and Primary Objective			Physical protection of fragile geoheritage (type localities, fossil/crystal beds) from over-collection and physical degradation.	Restoration of natural abiotic dynamics and landform integrity (e.g., degraded dunes, palaeo-meanders, karst systems).	Preservation and valorization of historical quarry faces, cut-slopes, cultural landscapes and industrial stone heritage.	Allowing natural morphodynamic and evolutionary processes to evolve without human interference, while preserving wilderness and absolute baseline conditions.
Mechanism/Intervention			Site fencing, regulated access, and erosion control measures around vulnerable outcrops. Application of transparent resins/polymeric consolidants to protect vulnerable surfaces while maintaining their visibility, alongside micro-fencing	Removal of artificial hard-engineering barriers to reactivate natural sediment transport and hydrological connectivity. Installation of eco-compatible elevated boardwalks or suspended footbridges	Structural stabilization and safety framing of human-modified rock faces and landscape for geo-education scopes.	Total absence of physical works; remote sensing monitoring, legal zoning constraints, access restrictions, and periodic scientific observation.
Secondary Objective			Preserves local soil profiles and creates undisturbed micro-refugia for specialized flora.	Enhances active surface dynamics and hydrographic networks while spontaneously increasing aquatic and riparian habitat diversity	Unveils and permanently exposes geological structure and stratigraphic beds, providing artificial nesting niches for cliff-dwelling fauna)	Safeguarding undisturbed natural habitats, maintaining wild ecological presence, and preventing the artificial acceleration of degradation caused by human presence.
Positive Outcome on	Geodiversity	Pedological		Processual (Physical) Hydrological	Structural Geological	Processual (Physical) Morphological
	Ecosystem Services	Biodiversity		Biodiversity	Biodiversity	Biodiversity and Wild Ecosystem Resilience

In this context, a fundamental distinction must be drawn not only regarding the relationship between geodiversity and biodiversity, but also concerning the specific environment in which the geological objects are located. The intrinsic link between geodiversity and biodiversity is a framework in which geodiversity provides the physical and chemical template for ecosystem processes and species evolution. As highlighted in recent synthesis papers by Beierkuhnlein et al. [71] and Tukiainen and Toivanen [72], geodiversity components directly support biodiversity across multiple scales by providing essential resources, habitat structures, and environmental refugia. While Tukiainen and Toivanen [72] focus on these foundational supporting roles, Beierkuhnlein et al. [71] further stress the bidirectional nature of the nexus, wherein biological feedback loops actively influence geodiversity over time. Recognizing these structural linkages justifies the inclusion of geodiversity assessments within holistic nature conservation strategies, ensuring that abiotic management directly reinforces ecosystem resilience and biological diversity. Beyond this biotic–abiotic nexus, every physical environment—whether natural or subjected to varying degrees of human modification—is characterized by specific evolutionary dynamics and distinctive geological and naturalistic features. These parameters directly govern landscape evolution, vulnerability, and weathering rate, thereby influencing the technical feasibility, long-term durability, and overall effectiveness of interventions, whether conservative, reconstructive,

or creative. In this context, Figure 2 highlights a decision-making framework for geoconservation management based on the biotic–abiotic nexus. Management priorities branch depending on the functional link between geodiversity and living systems. When abiotic features directly underpin living habitats, geoconservation management dynamically adapts to ecological imperatives and biological conservation priorities. In this context, protecting the supporting physical template ensures that broader geodiversity benefits as a secondary positive outcome. When abiotic features do not directly support primary biological components, management measures focus strictly on safeguarding geological heritage without primary ecological constraints, allowing biodiversity enhancements to emerge as a secondary positive outcome.

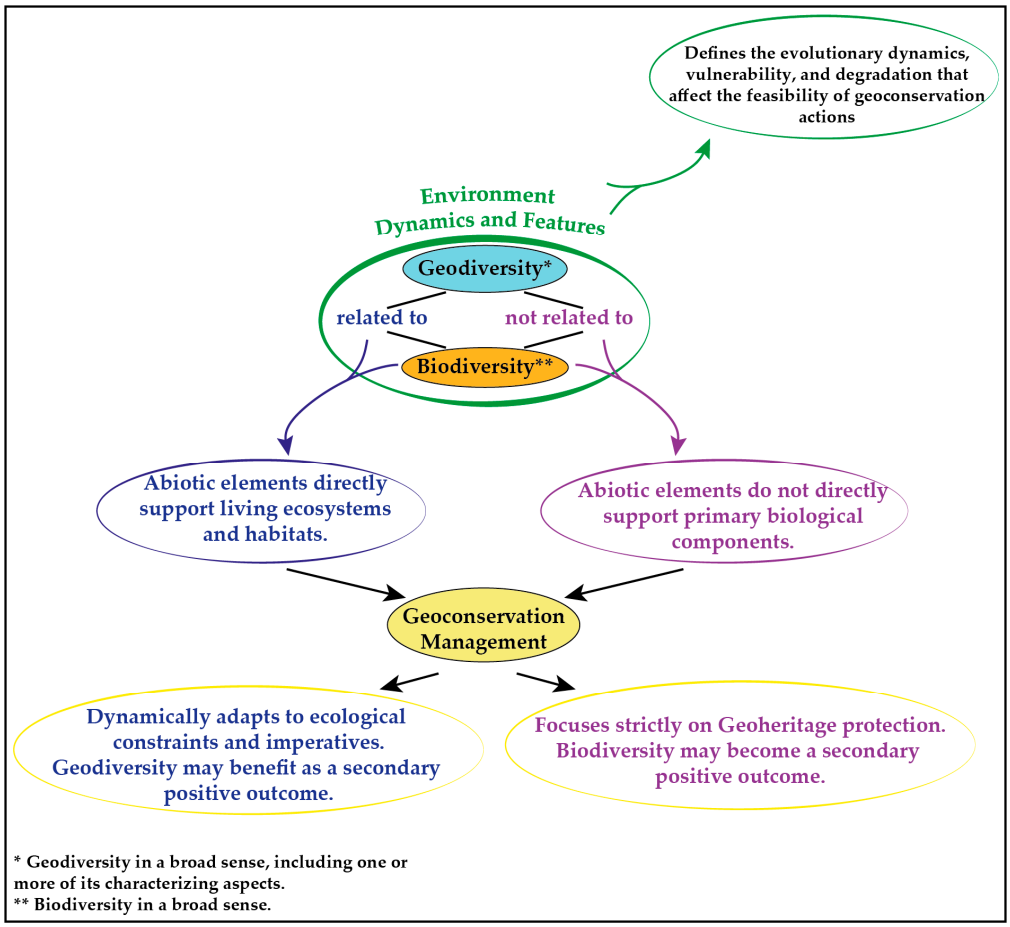


Figure 2. Conceptual decision-making framework for geoconservation management based on environmental dynamics and the biotic–abiotic nexus. Environmental dynamics and features define the evolutionary trajectories, physical vulnerabilities, and degradation processes that condition intervention feasibility. Geoconservation management branches according to the functional relationship between geodiversity and biological components: when abiotic elements directly support living habitats, management dynamically adapts to ecological imperatives, yielding geodiversity conservation as a secondary positive outcome; conversely, when abiotic features do not directly underpin living ecosystems, interventions focus strictly on geoheritage protection, with potential secondary benefits for local biodiversity.

In summary, this section provides a brief overview of geodiversity and geoconservation, proposing an operational framework structured into five primary groups and ten thematic classes (Figure 1 and Table 1). These classes address diverse abiotic dimensions, ranging from spatial and structural configurations to evolutionary dynamics and anthropogenic landforms. The text emphasizes the significance of the abiotic matrix as both a

protected physical asset and a foundational support system for biodiversity and ecosystem services, targeted through conservative, reconstructive, or creative interventions. Finally, management strategies are tailored to local environmental dynamics and the functional links between abiotic features and living systems—dynamically adapting to ecological imperatives when abiotic elements directly underpin habitats, or focusing strictly on geoheritage protection in other settings (Figure 2). Differentiating geodiversity classes within a site subject to geoconservation interventions serves two fundamental purposes. First, it enables rigorous, environment-specific scientific research; for instance, evaluating and quantifying geomorphological diversity in coastal systems requires diagnostic indicators and survey techniques that differ fundamentally from those used in karst environments, owing to their distinct physical characteristics and process-response mechanisms. Second, establishing clear taxonomies ensures that these technical distinctions are unambiguously communicated to land managers and practitioners tasked with executing conservation measures. Consequently, geodiversity components must not only be conceptually defined, but also quantitatively evaluated. This appraisal should incorporate evolutionary trajectories over spatial–temporal scales, economic feasibility, and broader socio-ecological impacts on both natural environments and local communities. Because the success of geoconservation interventions hinges on both technical accuracy and societal acceptance, scientific knowledge must be tailored to its specific audience. This necessitates a dedicated communication framework designed to address the diverse requirements of academic, management, and community stakeholders.

2.2. Communication Strategies in Geoconservation Actions

Communication plays a crucial role in geoconservation by acting as a framework that transforms scientific knowledge into effective management actions and public awareness. Without targeted communication strategies, geoconservation efforts may be misunderstood and perceived as unnecessary, disruptive, or overly costly. To bridge the gap between academic research, land management, and public perception, communication in geoconservation should focus on three main domains: Academic and Scientific Communication, Institutional and Technical Communication, and Public Communication and Community Engagement. These domains align with the framework established by Pescatore et al. [65] and further developed by Bentivenga et al. [73], which structures Applied and Popularizing Geoconservation into four interconnected macro-areas: Scientific Research, Administrative, Educational, and Tourist. Within this structure, the Scientific Research macro-area plays a vital baseline role by providing foundational materials and scientific data that feed into and support the administrative, educational, and tourist dimensions. The first domain focuses on the scientific community, researchers, and academic institutions. It establishes the theoretical, methodological, and empirical foundations of geoheritage analysis by emphasizing the identification, inventorying, and quantitative assessment of abiotic heritage. Its goal is to document intrinsic values, assess site vulnerability, and provide validated scientific evidence to establish conservation priorities. To achieve this, the language relies on a highly specialized scientific lexicon, dense syntax, and formal morphology designed to articulate complex geological processes, quantitative assessments, and standardized taxonomies. The second domain is tailored for decision-makers, public administrations, urban planners, engineering teams, and regulatory entities responsible for land management, corresponding directly to the Administrative macro-area. In this sphere, the language shifts away from purely theoretical terminology toward an operational and normative register. Using a precise administrative lexicon and structured syntax, this form of communication translates scientific findings into actionable spatial and engineering tools. This allows geoscientists to clearly convey technical constraints, hydrogeological risks, and safety thresholds required

by regulatory bodies to design durable, compliant, and environmentally compatible interventions. Specifically, it defines: (i) the rationale and operational goals of geoconservation interventions; (ii) the technical constraints and environmental vulnerabilities to guide project design and execution; and (iii) the key indicators and safety thresholds required by auditing and control agencies to evaluate structural durability, environmental compatibility, and regulatory compliance over time. The third domain targets the general public, local residents, tourists, and non-specialist stakeholders, addressing both the Educational and Tourist macro-areas. To reach this audience effectively, the communication style adopts a popularizing, accessible lexicon and direct syntax designed to break down technical, cultural, and sensory barriers. Rather than relying on abstract terminology, this domain translates complex Earth science into evocative, experiential formats—such as digital platforms, virtual tools, and interpretive routes. By explaining the reasons behind specific management actions (such as slope stabilization or restricted site access), public outreach prevents misunderstandings regarding project costs or landscape modifications, fostering civic pride, cultural connection, and long-term stewardship of abiotic heritage.

The cognitive sequence "Look > Observe > Understand > Know > Act" (Figure 3) reflects the structural phases of geoconservation identified by Pescatore et al. [65] and Bentivenga et al. [73]. At the same time, it illustrates the gradual development of public environmental awareness, showing how perception can evolve into understanding, knowledge, and ultimately active participation in environmental management. Although this sequence may appear straightforward, it highlights both the analytical process of scientific inquiry and the necessity of guiding non-specialist audiences toward appreciating abiotic heritage. Presenting geoconservation interventions without adequate contextual explanation risks reducing their perceived efficacy, leading the public to view them as intrusive or excessively costly. Conversely, effective communication fosters emotional and cultural resonance, encouraging active public involvement in territorial protection and safeguarding. This progression operates across two complementary dimensions.

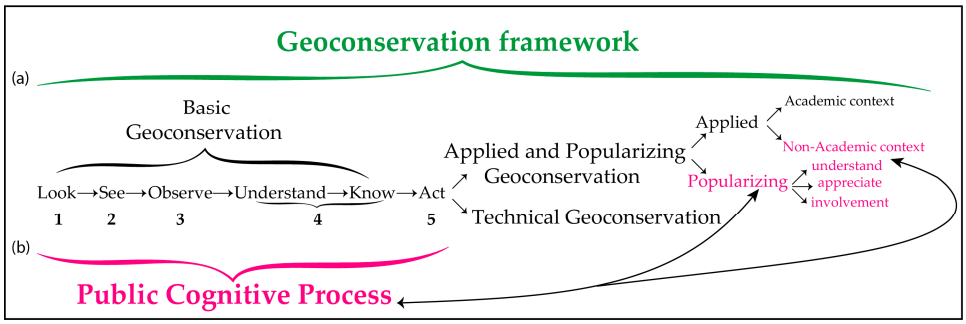


Figure 3. Integration of the cognitive sequence (Look > See > Observe > Understand > Know > Act) within the Geoconservation Framework (**a**) and the Public Cognitive Process (**b**). Note: The magenta color coding emphasizes the functional connection linking the Popularizing domain and the non-academic context of Applied Geoconservation (**a**) directly to the Public Cognitive Process (**b**), illustrating how communication outside pure academia serves as the primary interface to foster public understanding, appreciation, and active participation.

In the application to the Geoconservation Framework, the cognitive steps highlight the transition from baseline data collection to operational management (Figure 3a). Steps from 1 to 4 (Look > See > Observe > Understand/Know) correspond to the data collection and analytical phase (Basic Geoconservation). This stage progresses from a general visual scan of landforms to the systematic identification, inventorying, and quantitative assessment of geological features and dynamics, documenting their intrinsic scientific value. Step 5 (Act) represents the operational outcome, encompassing data processing, action planning,

and site interventions across the Applied and Popularizing Geoconservation and Technical Geoconservation domains.

Within this framework, the analytical and popularization sequence also expands into five distinct operational phases. A primary perceptive phase (Look), with an initial holistic observation focusing on the immediate spatial perception of the landscape. An analytical Phase (See), a deconstructive stage centered on identifying individual abiotic elements by disassembling lithological, structural, and geomorphological components. A dynamic-functional phase (Observe), represented by a process-oriented stage focused on identifying and monitoring active geomorphic processes, physical dynamics, and surface interactions shaping the landscape over time. A systemic phase (Understand and Know), an integrative stage focused on spatio-temporal dynamics and continuous interpretive modeling (Past-Future). By decoding past conditions (palaeo-dynamics), ongoing processes (active dynamics), and predictive trends (future scenarios), geoscientists establish solid scientific baselines for site management. An operational phase (Act) is an action-oriented stage centered on implementing protection, engineering, and spatial management interventions as rational, evidence-based outcomes.

In the application to the Public Cognitive Process (Figure 3b), this sequence defines the pathway that transforms a passive observer into an active guardian of heritage. As illustrated by the magenta color coding in Figure 3, both the Popularizing domain and the non-academic context of Applied Geoconservation (Figure 3a) operate as the primary interface connecting the theoretical geoconservation framework to the Public Cognitive Process (Figure 3b). This visual connection highlights how non-academic outreach—whether engaging local authorities or the general public—drives comprehension, appreciation, and direct involvement. Look > See > Observe > Understand: through targeted public communication using accessible language, passive viewing becomes active observation. The public is guided to recognize active evolutionary dynamics (e.g., weathering, erosion, sediment transport), translating abstract Earth science into comprehensible natural phenomena. Know > Act: comprehension solidifies into cultural and scientific awareness, driving behavioral change and actions. By understanding why a landscape evolves and where its vulnerabilities lie, the public respects site management constraints (such as remaining on designated trails or respecting restricted zones), accepts necessary conservation costs, and develops long-term civic pride and stewardship over abiotic heritage.

3. Methodological and Operational Framework

The enhancement of geological heritage is formally recognized, regulated, and implemented at both national and international levels. As outlined in Table 3, five sequential and interconnected phases designed to guide technical and administrative decision-making, from the initial basic diagnosis to the long-term management of the site/area, are necessary to ensure that geoconservation and enhancement interventions are scientifically sound, replicable, and feasible in practice.

The initial phase (Geo-Environmental Characterization) constitutes the physical diagnosis of the territory. The primary objective is to evaluate geological, geomorphological, and biological features and to assess the site/area's intrinsic vulnerability to active natural processes (e.g., erosion, active tectonic dynamics) and anthropogenic hazards.

Following the baseline characterization, the intrinsic and extrinsic values of the site/area are rigorously evaluated (GeoHeritage and Cultural Evaluation). This phase quantifies geological rarity, scientific and cultural representativeness, pedagogical potential, and interconnections with cultural heritage. This quantitative and qualitative assessment of scientific significance yields the essential scientific rationale required to provide rigorous justification for conservation interventions.

Table 3. Methodological framework and procedural phases for geoheritage assessment and territorial management. The table outlines the five main procedural stages—from Geo-Environmental Characterization to participatory governance—detailing key evaluation criteria, methodological scopes, and core strategic objectives for each phase.

Procedural Phase	Key Evaluation Criteria and Indicators	Methodological and Operational Scope	Strategic Objective
1. Geo-Environmental Characterization	Geological, geomorphological, and biological characterization. Intrinsic site/area vulnerability and degradation susceptibility. Morphodynamics and active geological processes	Comprehensive analysis of the site/area (e.g., exposure of rock faces, landform evolution, active erosional or tectonic dynamics).	Establish baseline conditions, identify high-priority geological features, and assess natural and anthropogenic hazard exposure.
2. GeoHeritage and Cultural Evaluation	Geological rarity and scientific representativeness. Cultural representativeness. Pedagogical and didactic potential. Interconnections with cultural heritage.	Quantitative and qualitative assessment of scientific significance and educational value.	Provide rigorous scientific justification for conservation interventions.
3. Regulatory and Administrative Alignment	Statutory protection regimes. Territorial spatial planning and zoning instruments. Institutional governance frameworks	Legal and institutional feasibility assessment, reviewing environmental protection mandates, land-use policies, and jurisdictional oversight.	Ensure regulatory compliance and facilitate the integration of geoconservation strategies into broader territorial planning.
4. Anthropogenic Pressure and Risk Assessment	Anthropic footprint and land-use changes Visitor carrying capacity dynamics. Risk of resource over-exploitation and degradation.	Analytical evaluation of human disturbance.	Formulate targeted mitigation measures, define visitor management protocols, and design ecological restoration actions.
5. Participatory Governance and Stakeholder Co-Design	Protected area authorities and municipal bodies. Local community groups and civil society organizations. Academic and scientific research institutions.	Engagement of multi-stakeholder consultation mechanisms involving local, institutional, and scientific actors throughout the planning cycle.	Develop a sustainable, participatory management plan that fosters community stewardship and promotes local socio-economic resilience.

Considering that the implementation of any physical or managerial intervention is contingent upon statutory feasibility, the third phase (Regulatory and Administrative Alignment) reviews environmental protection constraints, territorial spatial planning and zoning instruments, and institutional governance frameworks. This legal and institutional feasibility assessment ensures regulatory compliance and facilitates the integration of geoconservation strategies into broader territorial planning.

The human/nature interaction is a crucial key point. The fourth phase (Anthropogenic Pressure and Risk Assessment) critically evaluates the dynamic interaction between human disturbance and the site/area's vulnerability. It assesses risks originating from anthropic footprint, land-use changes, unmanaged visitor carrying capacity, and resource over-exploitation. The resulting analytical evaluation directly informs the for-

mulation of targeted mitigation measures, visitor management protocols, and ecological restoration actions.

Finally, long-term sustainability requires multi-stakeholder engagement (Participatory Governance and Stakeholder Co-Design). This conclusive phase establishes consultation mechanisms involving protected area authorities, municipal bodies, civil society organizations, academic research institutions, and local communities throughout the planning cycle. Co-designing management protocols fosters local community stewardship and develops a sustainable, participatory management plan that promotes local socio-economic resilience.

The completion of this operational protocol provides the analytical foundation required to define the subsequent intervention scenario, establishing a balanced equilibrium between non-renewable geoheritage protection and sustainable territorial development. Within this operational protocol, targeted geodiversity interventions are explicitly embedded to address specific conservation, restoration, and functional enhancement needs. To ensure their efficacy and operational precision, it is necessary to accurately define the intervention scenario. This requires the characterization of the site/area across key spatial, environmental, and typology-specific dimensions (Table 4a), including the following parameters.

Table 4. Analytical framework structure: (**a**) descriptive parameters of the territorial scenario and geodiversity components (geological, morphological, palaeontological, hydrological, etc.); (**b**) classification of geoconservation interventions by action type (preventive, conservative, regenerative, and non-action).

a	Scenario		
	Areal extension		
	Territorial context		
	Physical Environment		
	Spatial Positioning		
	Morphogenetic Landscape		
	Climatic Zone		
	Biodiversity		
	Geodiversity	Areal/Spatial	
		Geological	
		Morphological	
		Structural	
		Palaeontological	
		Mineralogical	
		Pedological	
		Hydrological	
		Processual (Physical)	
		Anthropogenic	
b	Geoconservation		
	Type	Action	Geodiversity
	Action type 1 Preventive 2 Conservative 3 Regenerative 4 Non-action		

- Areal Extension. Quantitative determination of the geographic surface area and spatial boundaries subject to analysis or intervention.
- Territorial Context. Classification of the spatial setting (e.g., natural and protected areas, urbanized/urban areas, anthropized environments).
- Physical Environment. Macro-physiographic setting (e.g., mountainous, hilly, lowland, or marine environments).
- Spatial Positioning. Spatial domain categorizations, distinguishing between epigean (surface) vs. hypogean (subsurface), and exposed/emerged vs. submerged conditions.
- Morphogenetic Landscape. Dominant process-response system and landform type (e.g., karstic, fluvial, glacial, glacio-fluvial, periglacial, hillslope, aeolian, or coastal landscapes).
- Climatic Zone. Macro- and micro-climatic framework governing active morphodynamic processes and degradation rates.
- Biodiversity. Assessment of ecological connectivity, biotic interactions, and biological habitats supported by abiotic substrate.
- Geodiversity Typology. Classification of the specific geological/geomorphological elements targeted for intervention, as systematized in Table 1.

In addition to defining the intervention scenario, a clear classification of the operational scope is also required (Table 4b). Depending on the site/area's vulnerability, conservation priorities, and degradation state, interventions are categorized into three distinct operational typologies.

Preventive/Maintenance Interventions: ongoing and periodic activities aimed at monitoring, protecting, and preserving existing geological features to prevent degradation and maintain long-term structural integrity.

Conservative Interventions: direct structural or protective actions designed to stabilize, safeguard, and protect fragile or threatened geoheritage elements from active erosional processes, climate impacts, or anthropogenic pressures.

Regenerative/Restorative Interventions: comprehensive restoration measures aimed at rehabilitating degraded sites, restoring natural dynamic processes, or functionally reintegrating the site/area into the surrounding landscape.

Non-Action/Passive Management Interventions: deliberate non-interference applied to highly delicate, dynamic, or pristine abiotic features (e.g., active badland dynamics or stabilized pristine rock faces), allowing natural physical processes to evolve unconstrained while avoiding human-induced disturbance.

The definition of (i) the type of intervention, along with (ii) the parametric characterization of the site or area, (iii) the various types of geodiversity listed in Table 1, and (iv) the aspects of geodiversity addressed by geoconservation interventions, establishes a technical framework that guides the decision-making process from project design to implementation.

The proposed methodology is explicitly designed to be scale-independent and flexible. Regarding territorial size and spatial contexts, the areal extent represents a key boundary condition defining the intervention scenario. The framework uses spatial scale not as a constraint, but as an operational parameter that directly influences intervention logistics, financial planning, spatial feasibility, and expected outcomes. For instance, applying a conservative action (e.g., monitoring or structural stabilization) to a discrete, single outcrop geosite vs. a large regional geomorphological landscape involves different operational tools (e.g., local sensor arrays vs. wide-area remote sensing), costs, and expected results, while maintaining the same analytical functional structure.

Regarding protection regimes, the framework operates as an adaptive management tool designed to align with existing legal and regulatory constraints (e.g., National Parks, Natura 2000 sites, or unprotected municipal areas). Higher protection regimes typically

favor non-invasive or strict conservation/preventive strategies (including "no-action" options to preserve natural dynamics), whereas lower protection regimes may prioritize active regenerative actions to build geotouristic infrastructure while establishing baseline geoconservation safeguards.

4. Practical Application and Results

Data from two representative sites—Craco and Pietra Maura (Basilicata Region, Southern Italy)—are presented to demonstrate the practical application of the proposed framework (Tables 5 and 6).

At present, specific quantitative assessment studies evaluating the geodiversity of these two sites are lacking in the literature. Therefore, the assigned qualitative values represent a synthetic operational rating rooted in the analysis of available scientific literature and in detailed considerations of the specific geodiversity classes. Specifically, the score for each geodiversity class was derived through a three-step analytical process.

- Bibliographic Data and Geological Significance Synthesis: re-evaluating existing scientific literature, geological maps, and technical reports to contextualize the site-specific geological significance, regional importance, structural framework, palaeontological features, and land-use characteristics of both areas.
- Expert-Based Field Assessment: evaluating the relevance, exposure, and functional role of each geodiversity feature, grounded in direct field observations, empirical survey data, and the authors' professional experience in territorial management.
- Ordinal Score Assignment: translating these integrated findings into a standardized three-tier scale (1 = Low relevance/presence; 2 = Moderate relevance/presence; 3 = High relevance/presence) to benchmark key components and directly guide targeted geoconservation interventions (including active options—Preventive, Conservative, Regenerative—as well as non-intervention strategies, i.e., "no-action", when natural process preservation or minimal interference is required).

Table 5. Parametric characterization and qualitative scenario assessment for the Craco compound geomorphosite and the Pietra Maura geosite. The qualitative evaluation uses a three-tier ordinal scale (1 = Low, 2 = Moderate, 3 = High) to rate the relative relevance of the ten geodiversity classes categorized across metric, abiotic, processual, and anthropogenic functional groups.

	Compound Geomorphosite	**Geosite**
	Craco	**Pietra Maura**
Scenario		
Areal extension	Mesoscale	Mesoscale
Territorial context	Urban and Urbanized	Natural and Protected
	Anthropized	
Physical Environment	Hilly	Mountainous
	Badlands	High-hilly
Spatial Positioning	Epigean	Epigean
Morphogenetic Landscape	Hillslope	Structural
	Gravity-driven landscape	Hillslope
	Fluvial	
Climatic Zone	Semi-arid Mediterranean	Temperate Sub-Mediterranean
Biodiversity	Low/Restricted	Moderate to High (protected area framework)

Table 5. *Cont.*

		Compound Geomorphosite			Geosite
		Craco			Pietra Maura
Geodivrsity	Areal/Spatial	3	High spatial heterogeneity	3	Localized high-value
	Geological	2	Plio-Pleistocene successions	3	Geological hotspot
					Anisian carbonate build-up
					Monte Facito Formation
	Morphological	3	Badlands	3	Structural cliffs
			Gullies		Rocky ridges
			Active landslide		
	Structural	3	Fractures and joints	2	Tectonic jointing
			Bedding planes		Bedding planes
					Localized faulting
	Palaeontological	2	Marine micro- and macro-fossils	3	Anisian marine fossils (brachiopods, bivalves, crinoids, algae)
	Mineralogical	1	Gypsum crystal aggregations in clayey facies	1	Calcite veins and authigenic mineralisations
	Pedological	1	Weakly developed, highly erodible soils	2	Shallow mountain soils
	Hydrological	1	Surface runoff	1	Fracture-driven karst drainage
			Ephemeral gully drainage		Seasonal surface runoff
			Piping		
	Processual (Physical)	3	Active mass movements	3	Weathering
			Intense slope erosion		Freeze–thaw breakdown
			Weathering		Rockfalls
	Anthropogenic	3	Ghost town	1	Minimal (ancient mountain paths, dry-stone walls)
			Abandoned masonry		
			Engineering works (AnthropoGeoHeritage)		

Table 6. Action-oriented geoconservation framework applied to Craco and Pietra Maura. Interventions are classified into three operational typologies (Action 1: Preventive, Action 2: Conservative, Action 3: Regenerative, Action 4: Non-action) and tailored to target geodiversity components. Note: Biodiversity is included in the framework to address ecological connectivity, although it is not classified as a geodiversity type.

	Geoconservation		
	Type of		
	Action	**Geodiversity**	
Craco	1	Morphological	Integrated in situ and remote-sensing monitoring of active slope dynamics and erosion rates
		Processual (Physical)	
	2	Anthropogenic (Historic and AnthropoGeoHeritage)	Structural stabilization, consolidation, and physical safeguarding of ruined historic masonry and fragile structures
	3	Anthropogenic	Geotouristic pathway design, removal of physical/cognitive access barriers, and installation of interpretive educational signage.
	4	Morphological	Allow active morphodynamic processes naturally evolving in highly dynamic and fragile natural badland slopes.
		Processual (Physical)	

Table 6. *Cont.*

	Geoconservation		
	Type of		
	Action	**Geodiversity**	
Pietra Maura	1	Palaeontological	Weathering rate monitoring, rockfall risk assessment, and installation of interpretive educational signage/paths.
		Geological	
		Structural	
	2	Palaeontological	Regulatory protection against illegal fossil collecting, over-exploitation, and unmanaged sampling
		Geological	
	3	Anthropogenic	Geotouristic pathway design, installation of interpretive educational signage, low-impact trail maintenance, protection of natural drainage, and habitat restoration along access routes.
		Processual (Physical)	
		Hydological	
		Biodiversity *	
	4	Morphological	Preserving natural stabilized structural rock faces
		Structural	

Action type 1 Preventive, 2 Conservative, 3 Creative/Regenerative, 4 Non-action. * Note that Biodiversity is not considered part of or a type of Geodiversity; the location in the figure is just a graphic choice.

Craco (Matera, Basilicata) represents an example of a ghost town and is formally considered a Compound Geomorphosite by Bentivenga et al. [73], defined as a complex site where features of geological and geomorphological interest closely coexist and interact with human and cultural heritage. Perched at the top of a prominent bedrock spur composed of alternating conglomeratic and arenitic beds overlying high-plasticity Pliocene-Pleistocene clays, the historic settlement was progressively abandoned following severe, prolonged slope instability and complex landslide dynamics [75]. The close spatial coupling between active erosional landforms (such as badlands, gullies, and landslide scarps) and the built urban infrastructure makes Craco an open-air laboratory for investigating active morphodynamic processes, human-environment interactions, and geoconservation strategies [73]. As detailed in Table 5, Craco exhibits maximum qualitative scores (Value = 3) for Areal/Spatial heterogeneity, Morphological landforms, Structural discontinuities, Processual (Physical) slope dynamics, and Anthropogenic heritage (including historical masonry and engineering stabilization structures defined as AnthropoGeoHeritage). Conversely, moderate qualitative scores (Value = 2) were assigned to the Geological and Palaeontological classes. Although the Pliocene-Pleistocene clayey-sandy deposits in the area exhibit excellent outcrop exposure and preservation, they do not represent the most benchmark or stratigraphically representative successions of the Southern Apennines, when compared to other regional type-sections. Finally, low qualitative scores (Value = 1) were attributed to the Mineralogical, Pedological, and Hydrological classes, reflecting their limited overall presence and thematic representativeness within the site's environmental setting. The geoconservation strategy outlined in Table 6 highlights: Preventive actions (Action 1) focused on Morphological and Processual (Physical) components via integrated in situ and remote-sensing monitoring of active slope dynamics; Conservative actions (Action 2) targeting Anthropogenic features through structural stabilization of historical masonry; Regenerative actions (Action 3) aimed at Anthropogenic elements to design safe geotouristic pathways, eliminate physical/cognitive access barriers, and install interpretive signage. In addition, a "no-action" strategy is deliberately maintained for highly dynamic and fragile natural badland slopes to allow active morphodynamic processes to naturally evolve.

Pietra Maura (Marsico Nuovo/Abriola, High Val d'Agri, Basilicata) is an outstanding Geosite recognized for its high paleontological, stratigraphical, and palaeoenvironmental significance within the Southern Apennines. The site is a key stratigraphic benchmark representing mid-Triassic (Anisian) carbonate build-ups and bio-clastic patch reefs embedded within the lower portion of the Monte Facito Formation (Lagonegro Basin) [76–78]. The outcrop features highly fossiliferous limestone facies containing exceptionally preserved marine macro- and micro-fossil assemblages, including brachiopods, bivalves, crinoids (Encrinidae Dujardin & Hupe, 1862), conodonts, and calcareous algae [77,79]. Located within a natural and protected mountain setting, Pietra Maura serves as an invaluable reference point for unraveling the early evolutionary stages and palaeogeography of the Mesozoic Tethyan domain [80]. As highlighted in Table 5, Pietra Maura scores highest (Value = 3) in Areal/Spatial relevance, Geological stratigraphy (Monte Facito Formation), Morphological structural cliffs, Palaeontological fossil assemblages, and active Processual (Physical) weathering. Moderate qualitative scores (Value = 2) were assigned to the Structural and Pedological classes, as these features—while well-expressed and clearly observable—do not constitute uniquely distinctive or exceptional traits when compared to other similar regional carbonate settings in the Southern Apennines. Finally, low qualitative scores (Value = 1) were attributed to the Mineralogical, Hydrological, and Anthropogenic classes: the first two are scarcely representative compared to other regional contexts, while the Anthropogenic class is essentially absent given the prevailing naturalistic and undeveloped setting of the geosite. Correspondingly, its operational management plan in Table 6 comprises: Preventive actions (Action 1) addressing Palaeontological and Geological elements through weathering monitoring, rockfall risk assessment, and educational path installation; Conservative actions (Action 2) protecting Palaeontological and Geological features via regulatory enforcement against unauthorized fossil collecting and over-exploitation; Regenerative actions (Action 3) encompassing Anthropogenic, Processual, Hydrological, and Biodiversity aspects through low-impact trail maintenance, protection of natural karst drainage, and local habitat restoration. Furthermore, a "no-action" approach is adopted for stabilized structural rock faces to avoid unnecessary invasive interventions that could alter their delicate equilibrium.

5. Conclusions

This paper presents an integrated theoretical and operational framework for geoconservation actions, discussing the gap between scientific geodiversity assessment, site-specific management, and public engagement. By deconstructing geodiversity into ten distinct thematic classes organized across functional groups, the framework moves beyond static interpretations of abiotic nature, providing a structured decision-support tool designed to enhance public awareness of the physical environment and its evolutionary dynamics. Concurrently, it equips land managers and decision-makers with tools and conceptual content needed to plan, prioritize, and execute targeted preventive, conservative, and regenerative interventions, while communicating them transparently to local communities. We would like to clarify that the proposed framework does not establish an absolute priority ranking or a quantitative significance score (where a high rating implies "higher conservation priority"). Instead, the 1–3 ordinal scale serves purely as a descriptive qualitative characterization of the presence and thematic representativeness of each geodiversity class within a given site. From a communicative and governance perspective, adopting a simple three-tier qualitative characterization (1 = Low, 2 = Moderate, 3 = High) enhances cognitive accessibility for non-specialist stakeholders, municipal planners, and local decision-makers who may lack specialized geoscientific backgrounds. Translating geodiversity characterization into actionable land-use policies requires flexible decision-making tools for local environmental managers. Grounded in site-specific characterization, this framework en-

ables planners to decide if, where, and how to intervene, as well as the strategic goal of the action: whether to protect existing features, enhance specific geodiversity classes regardless of their baseline score, or actively restore and create geodiversity in degraded settings where it is currently low (e.g., river restoration projects designed to increase vertical and horizontal morphological geodiversity—an avenue reserved for dedicated future research). Operationally, local authorities can embed this approach into municipal spatial planning through three administrative mechanisms: (i) spatial zoning and land-use constraints (e.g., defining protective buffers or intentional "no-action" dynamic preservation zones); (ii) targeted municipal budgeting, aligning public works funding with specific Preventive, Conservative, and Regenerative action lines; and (iii) institutional permitting workflows, integrating geodiversity criteria directly into Environmental Impact Assessments (EIAs) and participatory governance protocols.

The empirical applicability of the proposed model was tested through two contrasting case studies: the compound geomorphosite of Craco and the paleontological geosite of Pietra Maura. The qualitative-ordinal scoring system (ranging from Low-1 to High-3) enabled a rapid, transparent parametric characterization of both sites, capturing the stark contrast between highly anthropized, landslide-prone urban ruins and a pristine, fossiliferous carbonate site. This dual application highlights how the framework accommodates diverse territorial scenarios—from managing dynamic geohazards and historic architectural heritage (AnthropoGeoHeritage) at Craco to enforcing statutory protection over delicate paleontological records at Pietra Maura. A central outcome of this paper is the operationalization of the cognitive sequence Look > See > Observe > Understand > Know > Act, which provides a dual-purpose trajectory. In scientific and technical contexts, this sequence systematically structures the workflow from baseline empirical data collection (Look to Know) to evidence-based engineering and spatial management (Act). Simultaneously, when applied to public outreach—specifically through the interface connecting popularizing domains and non-academic contexts—the sequence delineates the pathway needed to translate complex Earth science into accessible natural phenomena. Guiding non-specialist audiences along this trajectory transforms passive landscape observers into informed, conscious citizens capable of appreciating not only the visible biotic heritage but also its fundamental abiotic foundation, respecting conservation mandates, and supporting territorial management initiatives. Furthermore, by integrating the biotic–abiotic nexus, the proposed model emphasizes that geoconservation management must remain dynamically responsive to environmental settings. Whether protecting pristine natural templates to sustain ecosystem resilience (such as Pietra Maura) or restructuring highly degraded, anthropized landscapes (such as Craco), the explicit differentiation between environment-specific geodiversity classes ensures both technical feasibility and socio-ecological compatibility. Strict numerical quantification and weighting of geodiversity were deliberately excluded from the initial scope of this paper, as the ordinal scores (1–3) were utilized solely to illustrate the parametric matrix. Because quantitative metrics are intrinsically contingent upon specific environmental regimes, climatic settings, and local morphodynamic processes, proposing a universal quantitative formula would risk oversimplifying territorial complexity. Instead, future research should focus on systematically reviewing existing quantitative assessment methodologies, categorizing them according to climatic contexts and environmental settings. Additionally, testing and operationalizing this framework across broader geographical domains and different statutory regulations—alongside developing metrics to measure public engagement efficiency along the Look-to-Act cognitive pathway—will further advance holistic nature conservation policies and long-term environmental sustainability.

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