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Review

Introduction to Biodiversity

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Abstract: Biodiversity constitutes the foundation of ecological balance and of the services that sustain human life, making its study and conservation fundamental in a context of increasing anthropogenic pressure and climate change. Research in this field has been oriented toward understanding diversity at multiple scales and designing effective conservation strategies. This review article aims to analyze the foundations of biodiversity and its conservation, the importance of genetic, species, and ecosystem diversity, as well as the role of ecological succession in the dynamics of biological communities. It argues that biodiversity, in all its dimensions, ensures resilience and ecosystem functionality, while succession provides the conceptual framework for understanding changes in community composition over time. The review asserts that the loss of diversity at any level weakens the adaptive capacity of natural systems and that successional processes are key to restoration and adaptive management. It concludes that integrating multiscale approaches to biodiversity with an understanding of successional dynamics is essential for designing more effective, sustainable, and adaptive conservation strategies in the face of global change scenarios.

Keywords: Ecosystem, Ecology, Successional dynamics, community.

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1. Introduction to Biodiversity

The term biodiversity comes from the combination of two concepts: Bio, which means life (from the Greek bíos). Diversity, which refers to the variety or difference between elements (Figure 1). Biodiversity is essential for maintaining resilient ecosystems in the face of threats such as climate change, human expansion, and habitat degradation. A global study analyzing the effects of climate change on biodiversity loss found that variables such as temperature, precipitation, and frequency of natural disasters are positively correlated with an increased number of threatened species; however, effective governance can reduce that impact. (Habibullah, Din, Tan & Zahid, 2021). Recent research highlights that protecting at least 30% of land, as proposed in the "30×30" target of the global biodiversity framework, could offer substantial gains for both species conservation and the provision of ecosystem services such as climate change mitigation and nutrient regulation.

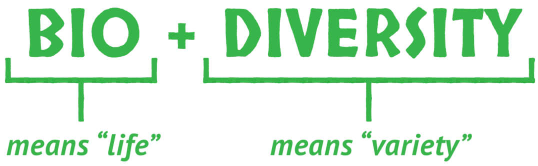

Figure 1. Origin of Biodiversity.

Beyond spatial protection, biodiversity plays a critical role in sustaining ecosystem services that support human well-being: food provision, soil stability, water regulation, pollination, pest control, among others. For example, a recent global review shows that ecosystems restored with native species tend to perform better in terms of carbon storage, erosion control, and water regulation compared to intensive plantations or monocultures, underscoring that not all restoration approaches are equivalent (Hua et al., 2022). Biodiversity has cultural and ethical value, as it is closely linked to the natural heritage of societies. Numerous studies emphasize that species loss not only affects ecological stability, but also the cultural identity of the peoples who depend on them for their traditions and ways of life (Dussex, 2023). Thus, protecting biodiversity means not only safeguarding ecological balance, but also preserving cultural diversity and the sustainable future of humanity.

Biodiversity forms the basis of the ecosystems that sustain life on Earth, providing essential services such as air purification, climate regulation, and food production. Between 40% and 80% of the global economy depends directly on ecosystem services provided by biodiversity, especially in less industrialized countries; losing biological diversity compromises these fundamental economic and social contributions. Biodiversity has not only utilitarian value, but also ethical, cultural, and normative value, which strengthens the argument for its comprehensive conservation. In this regard, studies emphasize that to meet global conservation commitments (such as those set out in the Kunming–Montreal biodiversity framework), it is not enough to declare protected areas, but rather to ensure that they are effectively managed, connected, ecologically intact, and equitably governed. (Robinson et al., 2024). Protecting biodiversity is not a luxury or a secondary option, but a central necessity for ecosystem health, food security, and resilience in the face of growing environmental threats.

Biodiversity loss has intensified due to human activities such as deforestation, pollution, and climate change. Recent reports warn that one million species are threatened with extinction, posing an unprecedented threat to natural systems and the services they provide. Biodiversity not only ensures the survival of species, but also guarantees the resilience of ecosystems in the face of environmental change. In this context, conservation becomes a global challenge that requires cooperation between governments, institutions, and communities (Dussex, 2023).

1.1 Concept of biodiversity: levels and dimensions

Biodiversity is the variability of life in its many manifestations and scales. Traditionally, three interrelated levels (Figure 1) are described: genetic diversity (within and between populations of the same species), species diversity (number and relative abundance), and ecosystem diversity (variety of habitats and landscapes). This formulation, popularized by the Convention on Biological

Diversity, emphasizes that it is not just a "count" of species, but a network of biological variation that sustains ecological processes and human well-being. These levels overlap with dimensions that allow us to better characterize this variability: taxonomic (who is present), functional (what they do and with what traits they do it), phylogenetic (what evolutionary history they share), and spatial and temporal (where and how they change over time). Together, levels and dimensions provide a robust framework for understanding and managing nature.

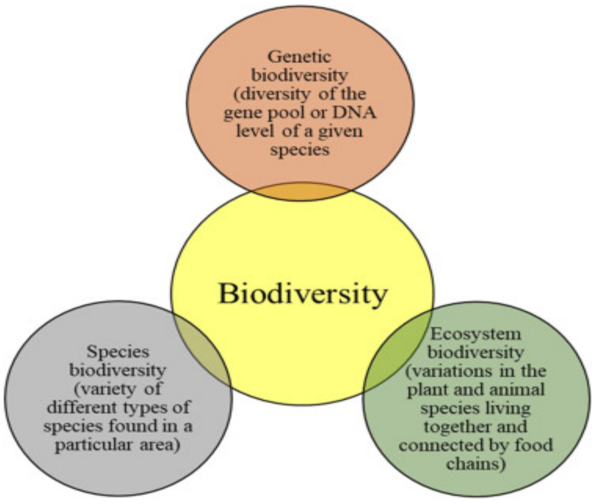

Figure 2. Types of biodiversity (Saleh et al., 2024).

Another line of definitions focuses on how we describe this variation. Noss (1990) proposed understanding biodiversity through three analytical dimensions (Figure 2): composition (what is there: genes, species, habitats), structure (how it is organized: abundances, connectivity, stratification), and function (what it does: energy flows, biogeochemical cycles, interactions). This approach is useful for conservation because it connects biological inventories with the design of protected area networks, restoration, and adaptive management.

Contemporary approaches broaden the definition to include nature's contributions to people, integrating not only taxonomic diversity but also functional and phylogenetic diversity. From this perspective, biodiversity encompasses the traits that enable species to fulfill ecological roles (pollinating, fixing nitrogen, dispersing seeds) and the evolutionary history that reflects their uniqueness; thus, conserving biodiversity involves safeguarding both the variety of life forms and the processes and interactions that enable the resilience of socioecosystems.

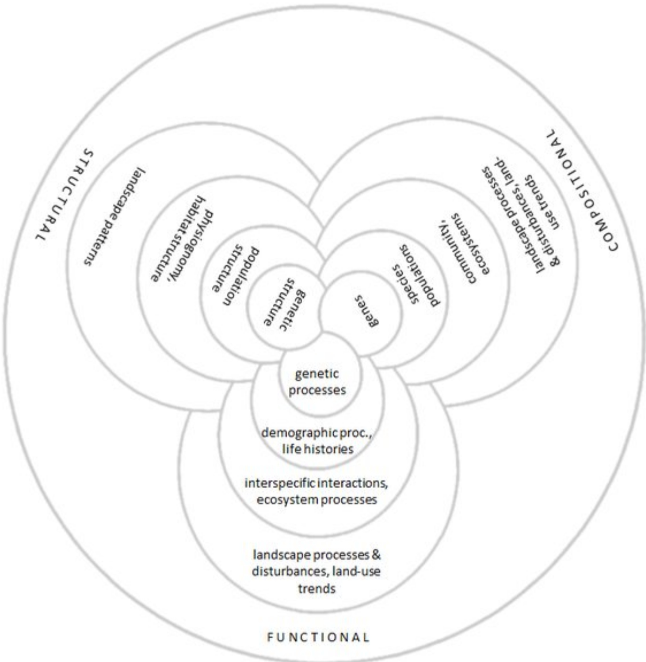

Figure 3. Three different dimensions of biodiversity: compositional, structural and functional. Redrawn (Noss, 1990).

1.2 Ecological, social, and economic importance

Biodiversity constitutes the natural infrastructure that sustains the functioning of ecosystems, human well-being, and economic activity. At the ecological level (Figure 3), it provides the processes that stabilize and make natural systems resilient (productivity, biogeochemical cycles, climate and water regulation). In the social dimension, it translates into direct and indirect benefits for health, food security, livelihoods, and cultural values, while reducing health and climate risks. From an economic perspective, it represents natural capital whose maintenance prevents losses and generates measurable returns when integrated into planning, accounting, and risk management. The following summary explores these three aspects—ecological mechanisms, contributions to people, and economic value—in greater depth to guide public policy decisions, investment, and project design with a focus on prevention, restoration, and adaptive management.

Ecological importance: Biodiversity underpins ecosystem processes and functions (productivity, nutrient recycling, water and climate regulation) and provides resilience to disturbances. The IPCC assessment (AR6, WGII) emphasizes that interactions between climate, ecosystems, and societies determine emerging risks and opportunities for climate-resilient development, highlighting the role of biological diversity in the stability of coupled nature-society systems.

The synthesis evidence also shows that the climate, biodiversity, and pollution crises are interdependent and must be addressed in an integrated manner to maintain ecological integrity. In terms of pressures, invasive alien species are recognized as a cross-cutting driver of degradation, with impacts on ecosystem functions and services in all biomes. At the outcome level, global indicators report average declines of 73% in vertebrate populations since 1970, with implications for critical ecological processes.

Social importance: Biodiversity is directly linked to public health (disease regulation, air and water quality, cultural/mental benefits) and food security through services such as pollination, the provision of wild foods, and soil protection. The WHO summarizes the evidence on the relationship between nature and health and recommends ecosystem-based approaches to mitigate climate and health risks.

In agriculture, about three-quarters of the most productive crops depend at least partially on pollinators, connecting conservation with nutrition and rural livelihoods. In addition, the IPBES Values Assessment (2022) demonstrates that making visible and valuing the diversity of nature's contributions to people improves public and private decisions, with co-benefits for equity and well-being.

Economic importance: From a development perspective, biodiversity is natural capital that sustains production, reduces risks (e.g., floods, crop failures), and generates economic returns when managed sustainably. The economy is embedded in nature and advocates for integrating natural capital into accounting and incentives. Recent estimates show that ecosystem services represent substantial economic values on a global scale and that their loss entails increasing costs. In practice, multiple countries are advancing in natural capital accounting and alignment with biodiversity and climate plans, using statistical frameworks and ecosystem accounts to inform policy, budgeting, and risk management.

1.3 Ecosystem diversity: types, functions, and resilience

Systematic conservation planning (SCP) provides guiding principles for selecting, configuring, and managing conservation networks: representativeness of biological features, complementarity between sites, sufficiency/persistence for long-term viability, efficiency (costs and conflicts), and functional connectivity (including climate) to sustain flows of organisms and processes. Recent advances emphasize that, to meet the Kunming-Montreal Global Biodiversity Framework, SCP must explicitly integrate restoration, adaptive management, and multi-objective goals for "nature recovery," as well as linking to criteria-based approaches such as Key Biodiversity Areas (KBAs) to ensure representativeness and persistence (Giakoumi et al., 2025; Plumptre et al., 2023; Butchart et al., 2024).

The spatial dimension is critical: operationalizing connectivity with actionable metrics in prioritization increases the robustness of portfolios and reduces the risk of population isolation (Beger et al., 2022). Another set of principles stems from the mitigation hierarchy—avoid, minimize, restore, and, as a last resort, compensate—with integrity rules such as additionality, "like-for-like" equivalence, permanence, limits for non-compensable impacts, transparency, and monitoring (Droste et al., 2022; Marshall et al., 2021).

Recent reviews show that governance and compensation design have diversified globally, but uncertainties remain about their effectiveness and traceability, so aligning ecological compensation with the GBF requires strict criteria and prioritizing avoidance over residual trade-offs (Kiesecker et al., 2023; Droste et al., 2022). Contemporary syntheses emphasize that many "no net loss" or "net gain" schemes fail if these safeguards are omitted, and recommend local, verifiable, and monitored frameworks. The principles of adaptive governance and management focus on rights-based and equity-based approaches for indigenous peoples and local communities (IPLC), as well as iterative learning in the face of accelerated ecological transformation. Evidence suggests that more positive ecological outcomes are associated with arrangements where IPLCs exercise equitable governance or shared control, which requires recognizing territorial rights and traditional knowledge in design and implementation (Dawson et al., 2024; Newing et al., 2023). Adaptive management frameworks such as RAD (Resist-Accept-Direct) help decide when to resist, accept, or direct ecosystem changes, integrating monitoring, experimentation, and decision thresholds; their articulation with reinforcement learning methods can make decisions under high uncertainty more robust (Lynch et al., 2021; Chapman et al., 2023).

1.4 Role of the environmental engineer in conservation

Contemporary conservation requires environmental engineers capable of integrating ecological science, monitoring technologies, and decision-making criteria throughout the project cycle. Their role articulates three fronts: (i) planning and evaluation with EIAs that apply the mitigation hierarchy, prioritize connectivity, and use biodiversity accounting/footprint tools to guide portfolios and purchases; (ii) design and implementation of nature-based solutions and restoration—alone or hybrid with gray infrastructure—to deliver verifiable ecological and hydrological performance (e.g., redesign of coastal defenses, mine closure with function recovery, watershed-scale flood mitigation); and (iii) monitoring and adaptive management supported by remote sensing, drones, and analytics/AI to measure results and activate management thresholds (Figure 4). This triad converts conservation and "net biodiversity gain" objectives into traceable, comparable, and auditable engineering decisions.

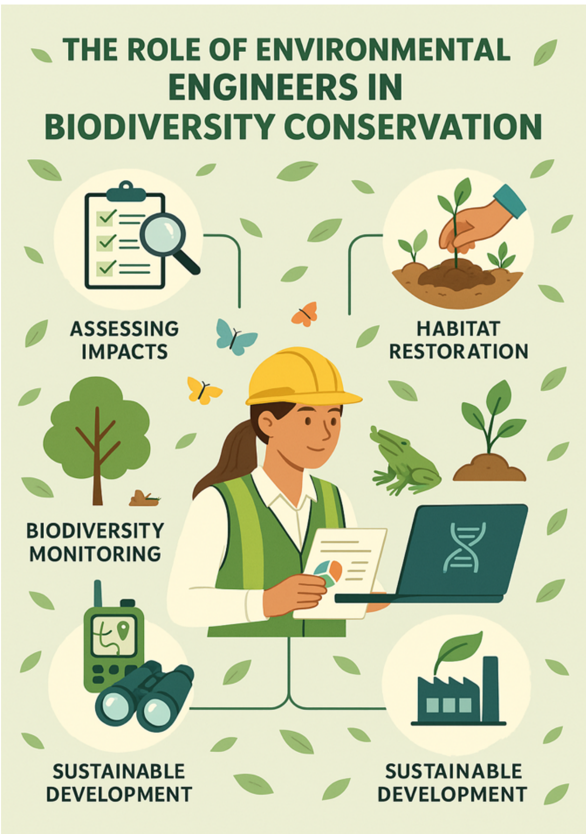

Figure 4. Role of Environmental Engineers in Biodiversity.

Environmental professionals incorporate biodiversity conservation throughout the project cycle: from planning and assessment, integrating the mitigation hierarchy into EIAs, ecological connectivity analysis, and spatial prioritization to ensure representativeness and persistence; to the design of cost-effective and traceable portfolios with biodiversity accounts/footprints. Recent literature shows operational ways to convert connectivity into actionable objectives within systematic conservation planning, reducing the risk of population isolation and promoting ecosystem resilience (Beger et al., 2022). In the design, implementation, and monitoring phase, the role focuses on deploying nature-based solutions (NbS) and pro-biodiversity engineering approaches, and on demonstrating results through indicators and adaptive monitoring. Synthesis evidence suggests that well-designed NbS generate concurrent benefits for climate adaptation and ecosystem health (Turner et al., 2022). In parallel, molecular biomonitoring with eDNA complements remote sensing and traditional methods, expanding spatial/temporal coverage and early detection of changes in communities (Lang et al., 2022).

Environmental professionals integrate conservation into the project cycle from the planning stage, using environmental impact assessments (EIA) that rigorously apply the mitigation hierarchy (avoid-minimize-restore-compensate) and specify biodiversity objectives and metrics (Cares et al., 2023; Dias et al., 2022). At the same time, they operationalize ecological connectivity and other spatial prioritization criteria in plans (Beger et al., 2022) and incorporate impact accounting throughout the life cycle by using biodiversity and linking it to natural capital accounts for engineering decisions and green procurement (Lindner et al., 2021; cf. critical review of methods in EIA; Castañeda-Aguilar et al., 2023). These approaches reduce net losses, facilitate BNG-type goals, and improve the traceability of ecological outcomes in infrastructure and land use.

In the design and implementation phase, environmental engineers develop nature-based solutions (NbS) and ecological restoration that maximize climate, hydrological, and biodiversity co-benefits and can be integrated with gray infrastructure (Suedel et al., 2022; Turner et al., 2022). Applied examples include the redesign of coastal structures to promote habitats and resilience to waves, storm surges, and erosion (Suedel et al., 2022); the restoration of mining deposits and degraded landscapes by optimizing ecosystem services and trade-offs (Zhang et al., 2023; Wang et al., 2023); and flood risk management through NbS at multiple scales, documented in recent manuals and technical books (Ferreira et al., 2021/2023; Bridges et al., 2021). These interventions require design rules, performance criteria, and post-construction monitoring to demonstrate sustainable ecological gains.

In monitoring and adaptive management, environmental engineers deploy observation and analysis technologies that increase the sensitivity and spatial/temporal coverage of monitoring: remote sensing and drones with deep learning for wildlife/habitats and change detection (Li et al., 2024), and eDNA/eRNA for inventories, early detection of invasive species, and community assessment, complementing traditional methods (Lang et al., 2022; Hassan et al., 2023). Combining these approaches with standardized indicators enables faster plan-do-check-act cycles, reduces uncertainty, and activates management thresholds, closing the loop between design, operation, and conservation outcomes.

2. Genetic, Species, and Ecosystem Diversity

Biodiversity is organized into three interdependent levels: genetic, species, and ecosystem diversity. Genetic variation is the substrate of adaptation and evolution; its erosion increases genetic load and reduces fitness (Ament-Velásquez et al., 2022; Dussex et al., 2023). Species diversity, measured by richness, evenness, and β-diversity, structures ecological networks and modulates ecosystem functioning (van der Plas et al., 2023). Ecosystem diversity—and its connectivity—buffers disturbances and sustains flows of organisms, energy, and matter (Beger et al., 2022). Taken together, greater biodiversity promotes long-term stability and resilience (Wagg et al., 2022).

2.1 Genetic diversity: the basis of adaptation and evolution

Genetic diversity—the variation of alleles and gene combinations within and between populations—is the immediate substrate of adaptation (Figure 5): it determines how much response natural selection can generate in the face of environmental changes. Two lines of evidence clearly demonstrate this. First, real-time evolutionary theory and experiments show that standing genetic variation (SGV) allows for rapid, polygenic responses, with many small-effect loci being rearranged under selection; This accelerates adaptation compared to the slower contribution of de novo mutations (e.g., in yeast under stress) (Ament-Velásquez et al., 2022; Fuhrmann, Prakash, & Kaiser, 2023).

Conversely, when populations become small, drift and inbreeding erode diversity and increase genetic load, reducing fitness and future adaptive capacity. A recent synthesis in Trends in Ecology & Evolution details how purging can eliminate some deleterious mutations, but often does not compensate for their accumulation, making genetic load management central to conservation (Dussex, Morales, Grossen, Dalén, & van Oosterhout, 2023). Furthermore, models and simulations show that density dependence can accelerate the loss of diversity and push populations toward the vortex of extinction, hindering so-called "evolutionary rescue" (Nordstrom, Hufbauer, Olazcuaga, Durkee, & Melbourne, 2023).

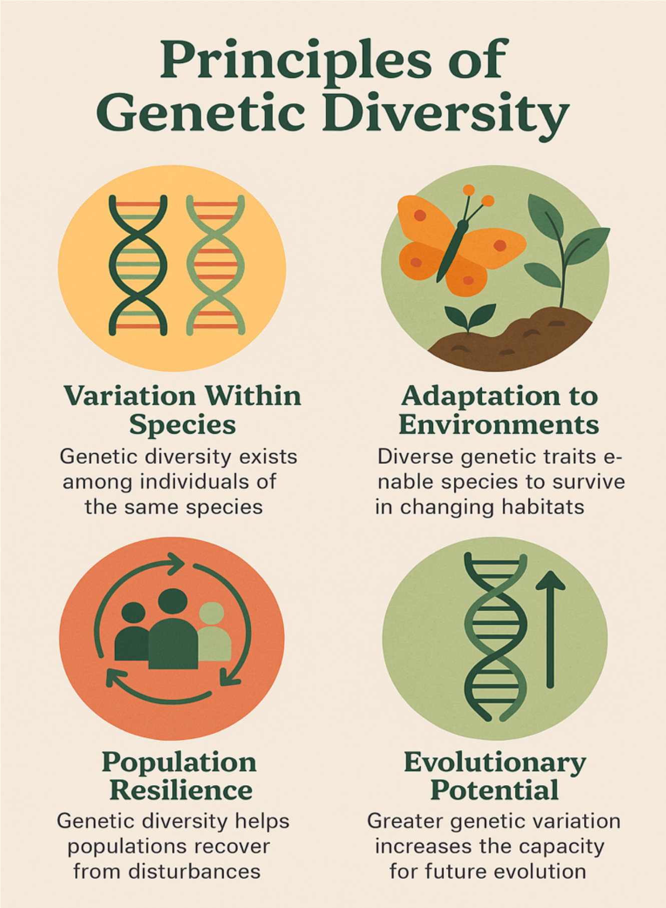

Figure 5. Genetic Diversity

Finally, genetic connectivity modulates adaptation: gene flow can contribute beneficial variants that favor local adaptation (or counteract it if it introduces poorly adapted genotypes). A recent review in the Journal of Evolutionary Biology summarizes patterns and effects of gene flow at different spatial scales and offers management implications (e.g., genetic assistance, genetic rescue) for maintaining or restoring the variation necessary for adaptive evolution in changing environments (Sexton et al., 2024). Taken together, conserving (and, when necessary, actively managing) genetic diversity is a necessary condition for sustaining the adaptation and evolution of wild populations under contemporary pressures.

2.2 Species diversity: classification and ecological relationships

Figure 6. Species Diversity

Species diversity refers to the variety and composition of species that coexist in a community (Figure 6), and its "classification" encompasses both the criteria for delimiting species (e.g., biological, phylogenetic, lineage concepts) and the approaches for organizing that diversity (taxonomic, functional, phylogenetic). In the last decade, integrative taxonomy frameworks that combine genomic, morphological, and ecological data have gained ground in reducing subjectivity in delimitation and standardizing taxonomic decisions, especially in groups with hybridization or polyploidy. These advances do not eliminate the pluralism of species concepts, but they do make assumptions and criteria in taxonomic practice more transparent. (Stankowski & Ravinet, 2021; Mallet, Dapporto, Tobler, & Papadopulos, 2022; "Species delimitation 4.0," 2023).

To measure species diversity, complementary components are used: richness and evenness (α–diversity), compositional turnover between sites (β–diversity), and regional diversity (ɣ). Recent research emphasizes that the relationships between β–diversity and ecosystem functioning are not universal: they depend on assembly scenarios and environmental gradients that modulate how species turnover translates (or does not translate) into production, stability, or resilience. This framework helps reconcile contrasting empirical results and interpret when spatial turnover informs large-scale processes and functions. (van der Plas, Hennecke, Chase, van Ruijven, & Barry, 2023).

Ecological relationships (Figure 7) between species—trophic, mutualistic, commensal, facilitative, or interfering—are represented as interaction networks whose properties (connectance, modularity, nesting, link strength) condition coexistence and community performance. A recent synthesis shows that ecosystem engineers (e.g., habitat builders, bioturbators) reconfigure network structure by modifying the physical environment and resources, with effects that can stabilize or

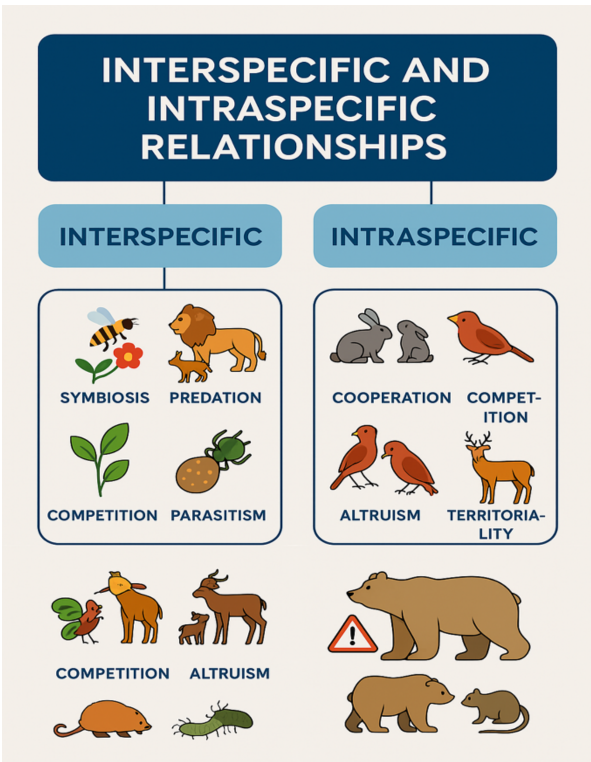

Figure 7. Ecological re;ationships.

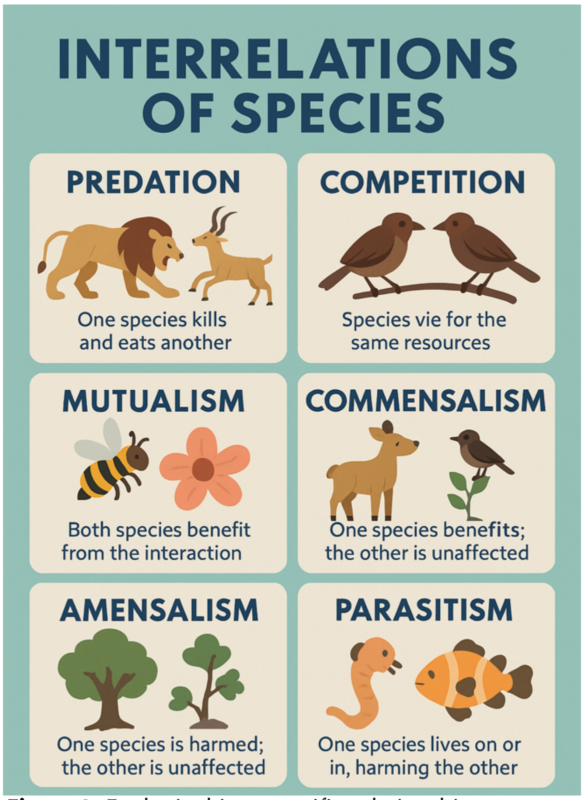

Figure 8. Ecological interspecific relationships.

destabilize communities depending on the engineering pathway and context. Incorporating these mechanisms improves the prediction of community dynamics and guides function-based management. (Sanders & Frago, 2024).

Species diversity and interactions (Figure 8) are linked to the stability (resistance, resilience, persistence) of ecological systems; recent theoretical advances integrate notions of stability and conditions for coexistence in networks, including higher-order interactions. At the same time, empirical assessments suggest that the importance of a species for "stitching" the network does not always coincide with its threat status, highlighting the need to conserve key interactions in addition to species. Together, these findings connect classification, metrics, and ecological relationships with conservation and adaptive management decisions. (Chen, Wang, & Liu, 2024; González-del-Pliego et al., 2024).

2.3 Ecosystem diversity: types, functions, and resilience

Ecosystem diversity (Figure 9) refers to the variety of habitats and landscapes (forests, wetlands, reefs, savannas, agroecosystems, among others) and their spatial and temporal heterogeneity; this diversity creates a "portfolio" of environmental conditions and processes that buffer disturbances and sustain multiple ecological functions and services at different scales. In climate and disaster risk management, ecosystem-based approaches show that diverse, interconnected mosaics increase socio-ecological resilience to floods, heat waves, and storms (Mukherjee & Shaw, 2021).

In terms of functions, recent evidence indicates that multifunctionality (e.g., productivity, nutrient cycling, water regulation, and carbon storage) is better explained by the functional diversity and structural diversity of communities than by species richness alone, especially in complex forests; these dimensions capture the complementarity of traits that enables simultaneous processes (Ouyang et al., 2023). At the global scale, the synthesis of ecosystem service values by biome

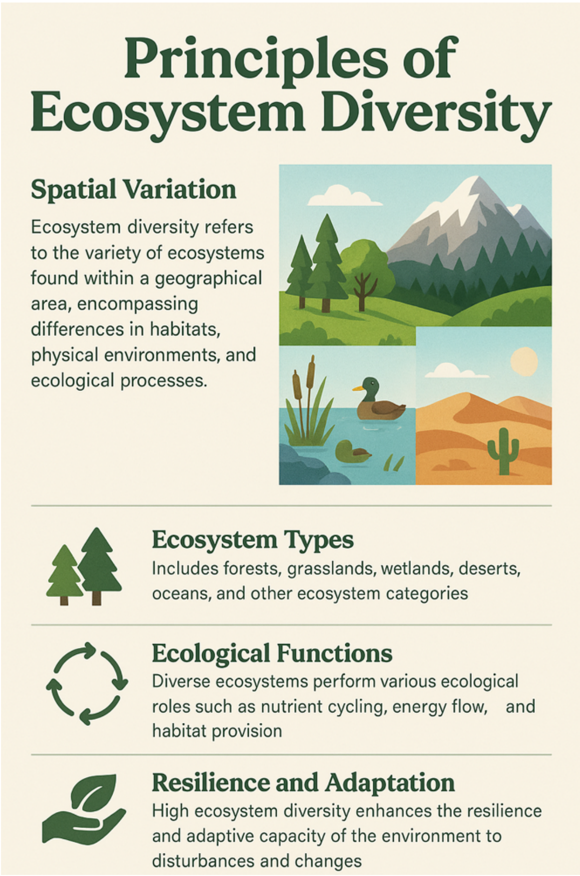

Figure 9. Ecosystem diversity.

confirms the economic magnitude of these functions and their relevance for decision-making (Brander et al., 2024).

The resilience of ecosystems—their ability to withstand and recover—increases with underlying biological diversity and ecological connectivity between patches. Long-term experiments in grasslands show that biodiversity–stability relationships strengthen over time via greater asynchrony and complementarity between species (Wagg et al., 2022). At the same time, integrating connectivity into spatial planning helps sustain flows of organisms and processes, reducing the risk of functional collapse in the face of global change (Beger et al., 2022).

In short, preserving the diversity of ecosystem types, their functions, and the connectivity that links them is a key strategy for building resilience and maintaining critical ecosystem services. Practical management combines restoration and nature-based solutions at the landscape scale with multifunctionality and service value metrics to guide priorities and avoid net losses (Mukherjee & Shaw, 2021; Brander et al., 2024).

2.4 Interconnection between the three levels of biodiversity

The interconnection between levels (Figure 10) of biodiversity—genetic, species, and ecosystem—describes a coupled system where genetic variation sustains species differentiation and persistence , and habitat and landscape diversity create the contexts that maintain that variability over time. Connectivity between patches and ecosystems not only favors the movement of organisms and flows of matter/energy, but also gene exchange that preserves the adaptive capacity of populations (Beger et al., 2022). At the same time, the composition and structure of communities determine how functions and services are expressed at the ecosystem scale (van der Plas et al., 2023).

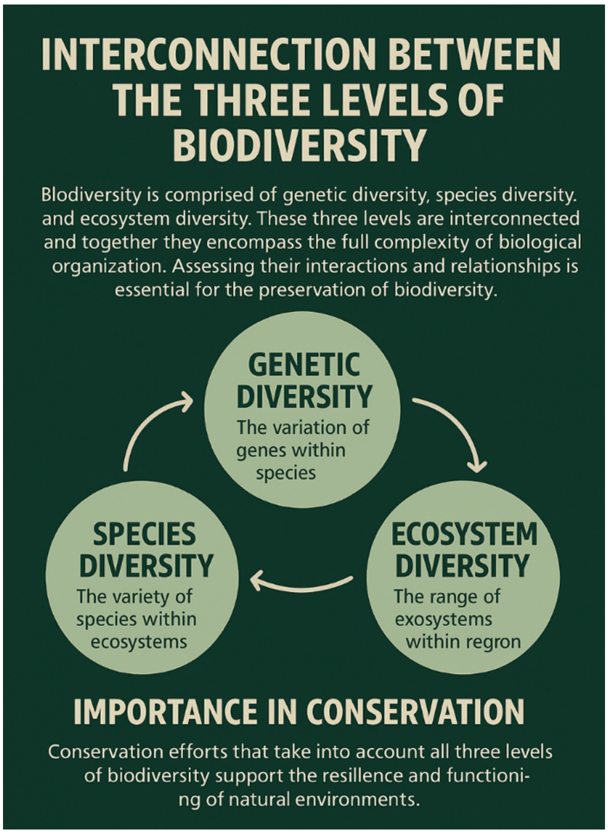

Figure 10. Interconnection Between Biodiversity

From the genetic to the species level, allelic diversity enables rapid adaptive responses—often polygenic—to environmental changes, preventing population collapses and sustaining coexistence in dynamic communities (Ament-Velásquez et al., 2022). When diversity is eroded by drift and inbreeding, genetic load increases and fitness decreases, reducing the probability of evolutionary rescue and increasing the risk of local extinction; managing this load is therefore an explicit goal of species conservation (Dussex et al., 2023).

From the species to the ecosystem level, richness and evenness—along with functional and phylogenetic identity—modulate stability and functioning through redundancy and asynchrony in responses to disturbances. Long-term experimental evidence shows that biodiversity–stability relationships strengthen over time, increasing community resilience (Wagg et al., 2022). However, the relationship between β-diversity (compositional turnover) and functioning is not universal: it depends on assembly mechanisms and environmental gradients, requiring contextual diagnostics (van der Plas et al., 2023).

From the ecosystem level back to the genetic level, habitat diversity and connectivity determine effective sizes, dispersal rates, and gene mixing; consequently, they influence adaptive potential and the probability of speciation or local differentiation. Spatial planning that integrates connectivity and representativeness reduces isolation, maintains ecological processes, and reinforces the virtuous circle of genes–species–ecosystems that underpins socioecological resilience (Beger et al., 2022).

3. Ecological Succession and Community Dynamics

Ecological succession (Figure 11) is the process by which biological communities change in structure and composition over time following a disturbance or on a new substrate, leading to more stable and diverse states in ecosystems. This phenomenon is inseparable from community dynamics, which encompasses how new species assemble, how they interact with each other and the environment, and how biodiversity, abundance, and resilience vary over time (Godoy, Soler-Toscano, Portillo & Langa, 2024). Factors such as stochastic processes (random seed deposition, ecological drift), environmental filters, and biotic interactions play decisive roles in this community assembly (Wang et al., 2024). In addition, the emergence of functional traits and dispersal limitations influence the successional trajectory, generating variability between sites even under similar conditions. In a context of global change, succession and community dynamics are central to understanding ecosystem recovery, species conservation, and the functional stability of ecosystems.

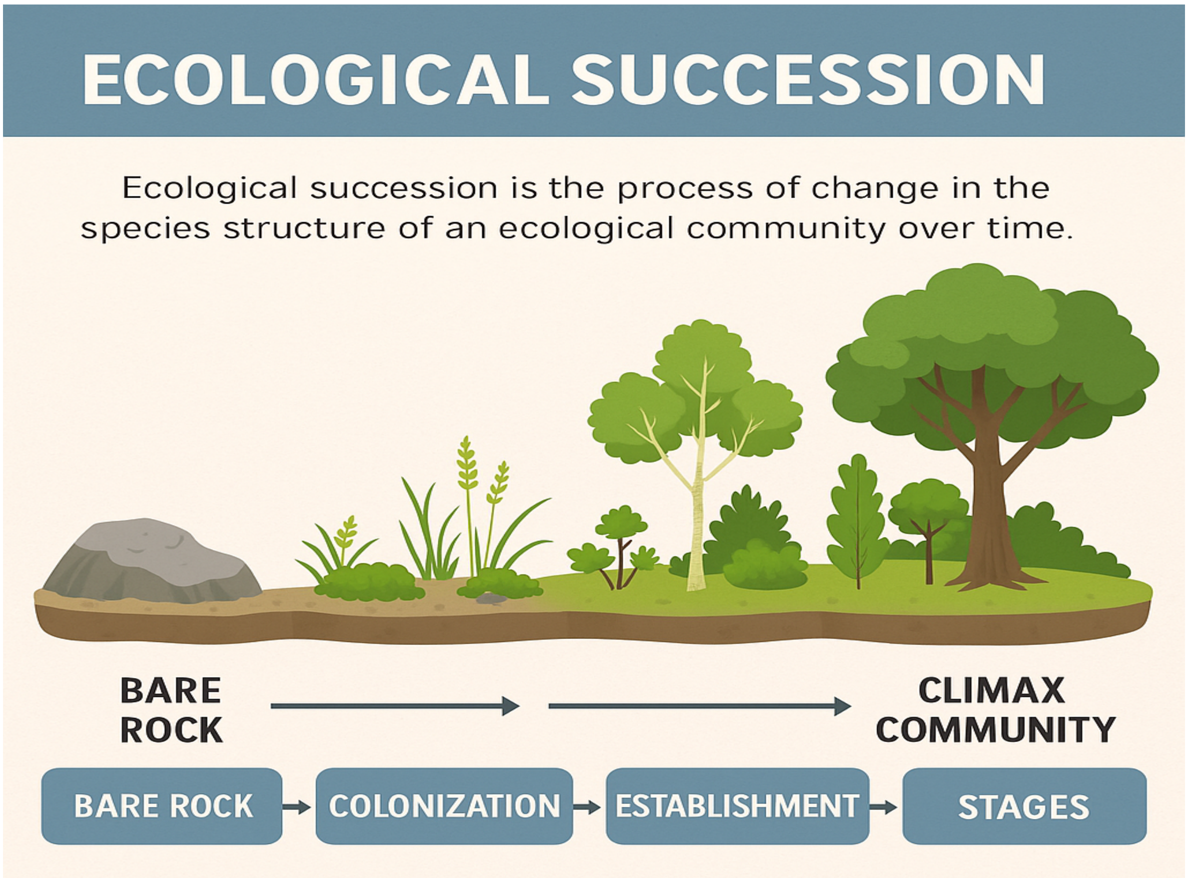

Figure 11. Ecological Succession Process

3.1 Types of succession: primary and secondary

Primary succession (Figure 12) occurs in environments that previously had no life or functional organic soil—for example, rocky surfaces newly exposed by glaciers, lava flows, or mineral deposits—where pioneer organisms (such as lichens, mosses, cyanobacteria) initiate soil formation through the accumulation of organic matter, weathering, and the establishment of microorganisms. This process is slow, as each stage depends on gradual environmental changes that allow species that are increasingly demanding in terms of nutrients and protection to establish themselves. Studies on the functional traits of pioneer microbes have shown that colonization capacity (dispersion), tolerance to abiotic stress, and the ability to fix nitrogen or capture nutrients in extreme conditions are key in these early stages of primary succession.

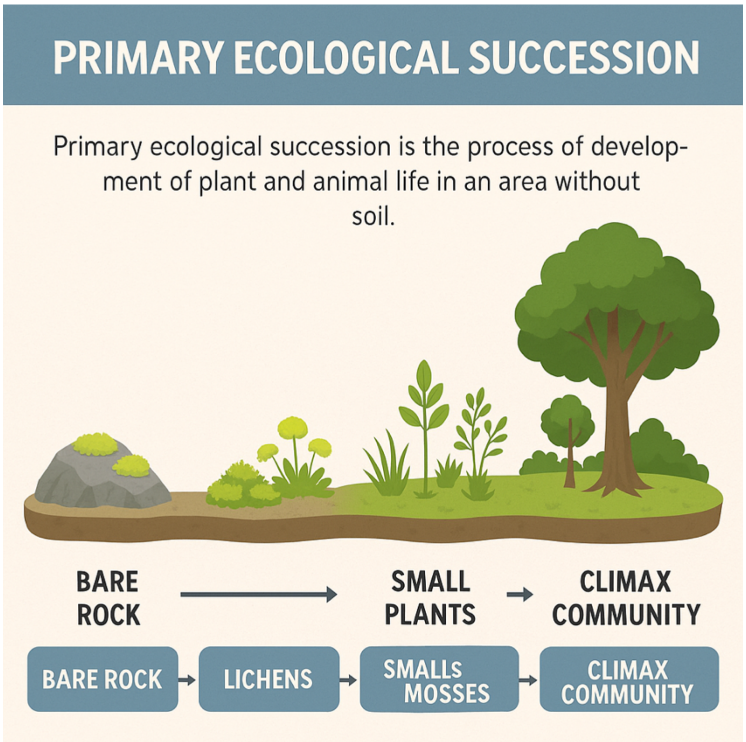

Figure 12. Primary Ecological Succession Process

Secondary succession (Figure 13) occurs in sites where soil is already present after a disturbance that removes part of the biota but leaves the substrate intact: fires, logging, agricultural abandonment, hurricanes, etc. Since seeds, dormant roots, and soil microorganisms remain, the processes of recolonization, biomass recovery, and diversity are faster than in primary succession. A recent example is the study by Poorter et al. (2021), which analyzed more than a thousand plots of secondary forest in the Neotropical tropics and found that the average functional values of the community (wood density, specific leaf area, nutritional content) evolve relatively quickly as succession ages, approaching the values of mature forests.

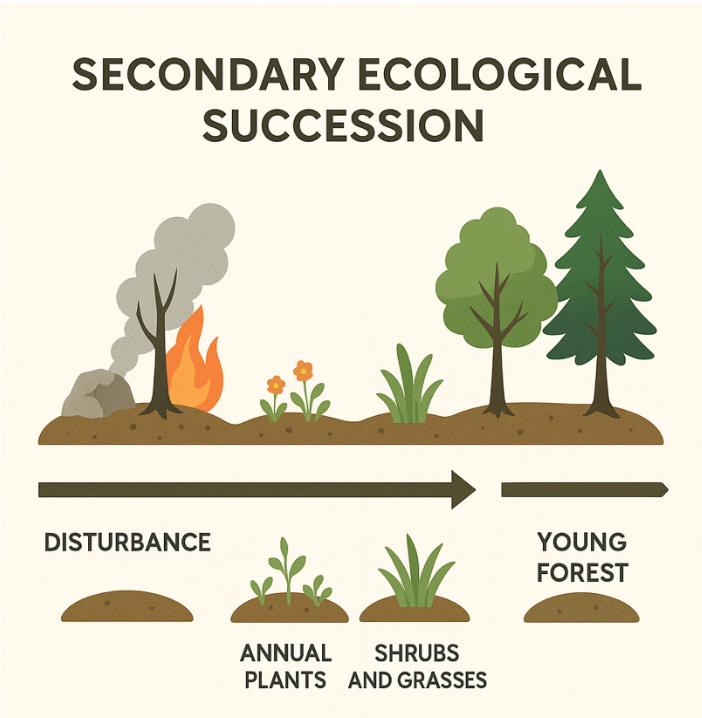

Figure 13. Secondary Ecological Succession Process

The differences between primary and secondary forests relate not only to the starting point (existence or absence of soil, presence of residual biota), but also to the ecological trajectory and dominant mechanisms. In primary succession, facilitation and external dispersal tend to play a more critical role: the first colonizers modify abiotic conditions (e.g., partial shade, moisture retention, accumulation of organic matter) to allow the arrival of more specialized species. In secondary succession, soil heterogeneity, the availability of seed reservoirs, competition between remnant and new colonizing species, and nutrient limitation strongly influence how recovery progresses.

Although both types of succession share the goal of approaching a climax community or a functional steady state, the time scales, pathways, and outcomes can vary greatly. In primary succession, changes can take decades to centuries to achieve complex structures and ecological stability; in secondary succession, forests can recover much of their biomass, diversity, and ecological functions within a few decades, provided there are no new severe disturbances. The study by Poorter et al. (2021) showed that, in tropical rainforests, some functional characteristics converge with mature forests already in the middle stages of secondary succession, although others (such as drought tolerance and wood density) may require longer periods to fully stabilize.

The mechanisms differ between types, but they share key processes: colonization, facilitation/competition, and abiotic and biotic filters. In secondary succession, plant–soil microbiota feedbacks change with successional stage and can reverse their effect (from negative to positive) on establishment, explaining why certain species dominate early stages and others late stages; this framework integrates disturbance legacies and community trajectories. Recent syntheses reexamine succession with temporal β-diversity metrics, connecting compositional reorganization with demographic processes (recruitment, growth, mortality) and highlighting that the directionality and speed of change vary with stage, disturbance type, and climate. In boreal forests, a critical review emphasizes that, despite increasing stochasticity under climate change, succession dynamics remain largely deterministic and predictable when legacies and disturbance regimes are incorporated, with direct implications for restoration and adaptive management.

3.2 Factors influencing succession

Abiotic factors, such as climate, nutrient availability, and soil conditions (pH, moisture, physical structure), are initial determinants in ecological succession. For example, studies of microbial communities indicate that soil carbon, nitrogen, and moisture content play a central role in determining which species dominate at different stages of succession. Similarly, a study of tropical forests found that the differentiation of ecological strategies of woody species at different stages of succession is linked to variations in soil fertility and precipitation. These abiotic conditions act as environmental filters, against which only species with certain tolerances can establish themselves, persist, or achieve dominance.

Another key factor is the dispersal and availability of colonizers. Proximity to seed sources, dispersal capacity (by wind, animals, water), seed size, and seed bank persistence affect which species arrive first in the disturbed area. In environments where the sediment or soil is new (such as after glacier retreat), the first species (pioneers) are usually those with high dispersal rates and rapid growth; their establishment can modify the physical environment, facilitating or restricting the arrival of successive species. Biotic interactions between species—competition, facilitation, predation, parasitism, mutualism—also modulate how succession progresses. A study of microbial communities in arid ecosystems suggests that interactions between microorganisms have a greater influence than direct environmental factors or geographical distance in structuring the community.

In plant succession, it has been observed that initial species can modify the microclimate (e.g., shading, moisture retention), which can facilitate the colonization of species that are less tolerant to abiotic stress; the opposite occurs when pioneer species compete for resources and exclude others. Stochastic factors (randomness) and disturbances (natural or anthropogenic) strongly influence both the rate and trajectory of succession. Processes such as ecological drift, dispersal limitations, random climate variability, fires, floods, avalanches, or human disturbances can alter the expected direction of succession. In addition, global warming can change the relative importance of deterministic processes (such as environmental filtering) versus stochastic processes, modifying both which species can establish themselves and how quickly they do so.

3.3 Succession and climax models

Ecological succession is a dynamic process whereby biological communities change over time, from pioneer stages to more complex and stable communities. Classic succession models—facilitation, inhibition, and tolerance—remain relevant for understanding how some species modify environmental conditions by favoring, restricting, or being neutral to the establishment of others. Recent studies indicate that these models are not mutually exclusive, but rather coexist in a complementary manner in different ecosystems and time scales (Li et al., 2022). The concept of ecological climax refers to the final state of equilibrium toward which succession tends under stable environmental conditions. However, current research highlights that this climax is not a fixed point, but a dynamic state subject to variations in climate, soils, and recurrent disturbances. Thus, the notion of climax is redefined as a flexible condition that reflects both the resilience of the community and its ability to adapt to global changes (Dejene et al., 2021).

In boreal and temperate forests, functional and phylogenetic diversity has been shown to increase progressively during succession, modifying biotic interactions and the community's resilience potential. This pattern suggests that the complexity of community assemblages at climax does not depend solely on elapsed time, but also on environmental and anthropogenic factors that shape the successional trajectory (Chai et al., 2021). These findings support models of succession where climax states are multiple and contextual, rather than unique and universal.

Recent research on aquatic and terrestrial ecosystems shows that successional progress and approach to a climax can be predicted using models that integrate abiotic factors—such as nutrients, radiation, and temperature—with biotic interactions. These approaches suggest that climax can be better understood as a dynamic balance between internal ecological processes and external pressures (Graco-Roza et al., 2021; Krause et al., 2022). Contemporary succession theory therefore recognizes the importance of environmental variability and uncertainty as essential components in the definition of climax.

3.4 Role of succession in ecological restoration

Ecological succession provides an operational framework for restoration because it describes how communities and their functions change after a disturbance, allowing decisions to be made about when to “let nature take its course” and allow natural regeneration to occur, and when to intervene. In landscapes where there are intact sources of propagules and functional processes, secondary succession can restore key interactions and ecosystem services at relatively low cost; For example, restoring seed dispersal by wildlife during passive regeneration speeds up species turnover and convergence toward mature forests (Estrada-Villegas et al., 2023; Lohbeck et al., 2021). In contrast, when there are “bottlenecks”—propagule limitations, impoverished soils, herbivory, or frequent disturbances—it is necessary to combine plantings, enrichments, or applied nucleation to redirect successional trajectories (Fischman et al., 2024; Procknow et al., 2025).

The decision between passive and active restoration depends on the socio-ecological context and explicit goals. A landscape analysis showed that, in the Carpathians, passive forest expansion covered large areas and complemented active actions, suggesting more cost-effective mixed portfolios (Hartup et al., 2022). In subtropical forests, successional gradients are reflected in soil recovery (structure, C and N, microbial biomass), which are sensitive indicators for monitoring progress toward more functional states. Tools such as natural succession indices allow sites to be prioritized and investments to be reallocated according to "successional potential" under different climates (Gui et al., 2025).

Integrating ecological theory improves design: hierarchical facilitation, biodiversity-function theory, and dispersal models help select "nodal" species (nurse pioneers, dispersers, engineers) and sequence interventions to accelerate trajectories (Silliman et al., 2024; Allison, 2023). In coastal dunes, for example, planting a stress-buffering pioneer can increase the growth and establishment of the climax species, provided that disturbance dynamics allow it (Fischman et al., 2024). Finally, recent standards and syntheses emphasize that success is evaluated as progress along multiple trajectories, measured with vegetation and soil indicators, and adaptively adjusted to local constraints and biodiversity and resilience objectives (Florentine et al., 2023; Procknow et al., 2025; Lohbeck et al., 2021).

4. Conclusions

Biodiversity is central to environmental engineering, as it ensures the provision of fundamental ecosystem services such as water regulation, air quality, and soil fertility. In this professional field, understanding biodiversity patterns allows for the design of projects that not only mitigate environmental impacts but also strengthen the resilience of ecosystems in the face of climate change and anthropogenic pressure. In this way, environmental engineering becomes a discipline that integrates biological knowledge with the design of sustainable solutions.

Genetic, species, and ecosystem diversity are pillars of environmental planning, as they ensure the adaptability of living systems in the face of disturbances. For environmental engineers, recognizing these scales of diversity is key when assessing impacts, proposing compensation measures, and designing management plans that maintain or restore ecological integrity. Thus, environmental management takes on a holistic vision that recognizes the interdependence between levels of biological diversity.

Ecological succession and community dynamics offer an invaluable theoretical and practical framework for the restoration of degraded areas. From an environmental engineering perspective, applying these concepts allows us to project the future evolution of intervened ecosystems, estimate their recovery capacity, and select active or passive restoration strategies. Furthermore, understanding how communities are structured over time is essential for designing interventions that promote resilience and reduce maintenance costs in restoration projects.

Finally, integrating biodiversity and succession approaches into environmental engineering strengthens the capacity to meet the challenges of sustainable development. By incorporating these tools, environmental engineers not only protect natural systems, but also provide innovative solutions that balance human well-being with ecological conservation. In conclusion, these topics are not only academic fundamentals, but strategic components for professional practice, environmental decision-making, and the construction of more sustainable societies.

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