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REVIEW

Engineering Resilience: Novel Approaches in Ecosystem Restoration

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ABSTRACT

Climate nonstationary and exacerbated disturbance regimes, as well as ubiquitous human alteration of landscapes and seascapes, are increasingly challenging ecosystem restoration. In this scenario, restoration strategies based on static reference states, or short-term structural goals, tend to provide delicate results that fail when subjected to extreme events, new stress factors, or changing baselines. The current essay is a synthesis of the new paradigm of engineering resiliency towards ecosystem restoration that combines the principles of design-oriented engineering and theories of ecology of complexity, thresholds, and adaptive capacity. We explain conceptual differences and complement between ecological and engineering resilience, as well as highlighting resistance, recovery trajectories, and adaptability as aspects of the operation of performance. We also study fresh resilience-enabling strategies, such as nature-based solutions and gray-green systems, ecological engineering and system-level design, digital technologies of monitoring and prediction, and adaptive management based on the concept of feedback-control. In the land, freshwater, coastal, and urban systems, we evaluate such strategies underway to increase the integration of persistence of functions and provide ecosystem-vitality despite disturbance, as well as the inescapable problems related to scaling, governance, equity, and long-term sustainability. Last but not least, we define the areas of priority in research, such as the standardized measures of resilience, long-term monitoring, uncertainty-aware models, and responsible innovation to reduce unintentional ecological and social effects. Reconceptualizing restoration as a performance-based design challenge that is enshrined in coupled human-natural systems, engineering resilience provides

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a transdisciplinary, rigorously grounded approach to creating ecosystems that survive and adapt in a fast-changing world.

Keywords: Engineering Resilience; Ecosystem Restoration; Nature-Based Solutions; Adaptive Management; Gray-Green Infrastructure

1. Introduction

Blistering and extensive destruction of ecosystems has become one of the characteristics of the twenty-first-century environment[1,2]. Due to climate change, alterations in land-use, pollution, and depletion of biodiversity, natural systems operating at the terrestrial, freshwater, coastal, and marine levels are under unprecedented pressure, which is beyond the range of variation experienced historically. As a reaction, the restoration of ecosystems has become the main focus of global agendas on sustainability, such as the United Nations Decade on Ecosystem Restoration and national climate adaptation plans. Nevertheless, with deep investments and scientific developments, there are several cases where a restoration project never yields the same results, especially when the environmental uncertainty and disturbance intensity increase. Such constraints underline the necessity to approach the system of restoration of ecosystems to a specific predetermined state of history with a paradigm shift to designing systems that are resilient to changes and adaptable, able to regenerate in the fast-evolving world[3–5].

Resilience has consequently become a central principle in the modern Restoration science. Initially associated with the discipline of ecology, resilience is loosely the ability of a system to withstand disruption without losing its fundamental structure, functioning, and feedbacks[6]. Ecological resilience pays more attention to the stability domains of a system, thresholds, and regime shifts, whereas the traditional ecological concept of engineering resilience pays more attention to how resistant the system is to disturbance and how fast it can recover the equilibrium after perturbation. To illustrate the conceptual convergence and divergence of ecological and engineering resilience, **Figure 1** presents a map highlighting the key attributes of each resilience type and their integration in ecosystem restoration efforts. Although the ecological resilience concept has become very popular in managing the environment, its application in restoration practice has remained general, qualitative, or retrospective. Engineering resilience, on the other hand, has quantitative, design-based instruments previously applied in such engineering fields as civil, mechanical, and systems engineering, but not yet applied in ecosystem restoration[3,7–9].

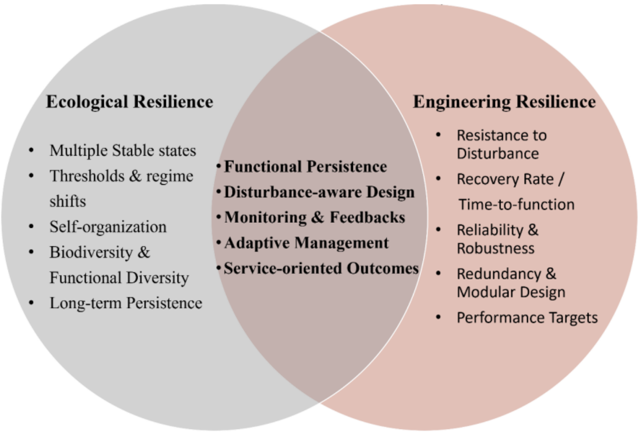

Figure 1. Conceptual map linking ecological resilience and engineering resilience in ecosystem restoration.

Other conventional methods of restoring ecosystems have mainly been based on the old-fashioned reference conditions, species composition goals, or structural standards to historical baselines. Although these methods have been successful in comparatively steady settings, they are also being surpassed by the non-stationary climate, disturbed disturbance regimes, and emerging ecological structures. The restoration projects, which fail to consider stressors that might occur in the future, can be successful in the short run, but have low durability, high maintenance, or be vulnerable to collapse after extreme events like droughts, floods, fire, or outbreaks of invasive species. Such results highlight a key deficiency, namely, restoration has frequently focused on what ecosystems should appear to be, as opposed to the functioning of ecosystems and the manner in which ecosystems react to distress [10].

Resilience engineering provides an additional perspective to interpret ecosystem restoration not as an ecological reconstruction exercise, but as a design problem [11]. In this respect, the ecosystems are treated as complex adaptive systems where performance in the case of disturbance can be improved through the deliberate design, feedback, redundancy, modularity, and adaptive capacity. Industrial engineering fields have long faced similar issues with the infrastructure systems, and resilience, recovery time, and flexibility are the key performance indicators. When these principles are translated into ecological settings, the restoration strategies that are designed can explicitly consider the dynamics of disturbance, sleep, and wake processes in the system, as well as the functionality of the system over the longer term [12,13].

However, over the last few years, ecological engineering and nature-based solutions, as well as hybrid gray-green infrastructure, have started to fill the gap between ecological theory and engineering practice [14]. To illustrate, adaptive hydrological controls and real-time monitoring are gradually introduced to engineered wetlands that are to be used in flood reduction and water purification. Coastal reclamation initiatives are currently combining living shoreline and constructs to increase wave attenuation to sustain biodiversity. The re-conceptualization of urban ecosystems is being done as multifunctional systems that deliver ecosystem services, climate regulation, and social benefits and remain resilient to anthropogenic pressures. These trends have indicated a more general move toward resilience-oriented restoration, but there is still no general conceptual and methodological framework [15].

To make matters worse, there is an increasing complexity of the socio-ecological systems. Ecosystems are not standing alone and are fully integrated with human activities, governance frameworks, and economic engines. Restoration initiatives should thus be run in coupled human-natural systems where social approval, policy limitations, and resources influence the design and results. The engineering of resilience and its focus on integrating systems, providing measures of performance, and implementing management-by-objectives are especially well-positioned to handle these interdependencies. Resilience-based designs can also be changed over time as feedbacks of stakeholders, monitoring data, and learning experience are incorporated in the designs to facilitate adaptation to the evolving environment and social conditions [16,17].

The possibilities of engineering the resilience of ecosystem restoration are also extended by technological advances. Continuous monitoring of the conditions of ecosystems and environmental stress reactions can be accomplished with remote sensing, unmanned aerial systems, environmental sensors, and digital twins. With the help of machine learning and artificial intelligence, it is possible to predict the effects of disturbance and recovery paths and to implement proactive management instead of reactive intervention. New materials science and biotechnology, including biodegradable structures, engineered substrates, and assisted evolution techniques, provide new means of improving ecosystem functionality and resilience. Nevertheless, the ethical, ecological, and governance aspects are also discussed by these innovations that should be thoroughly considered [18].

Although there is an emerging interest in resilience-based restoration, the literature is still scattered across fields, case studies, or a limited range of technologies or ecosystems. Very little literature integrates concepts of engineering resilience with ecological theory in a manner that is easily accessible to practitioners in the field of restoration, policymakers in the field, and researchers of the interdisciplinary approach. Furthermore, the absence of unified metrics and systems of evaluation of resilience complicates comparing the results of restoration and constrains the transferability of best practices. These gaps are becoming increasingly widespread as efforts towards restoration become increasingly more massive around the world.

This review will serve as a synthesis of engineering resilience as a new framework of ecosystem restoration, an innovative approach to ecosystem restoration, a new development of methodology, and applications in a variety of ecosystems. Particularly, the aims of the present review are to: (i) explain the conceptual foundations of engineering resilience during ecological settings; (ii) review new engineering-based strategies that promote ecosystem resistance, recovery and adaptability; (iii) evaluate applications and case studies that exhibit resilience-based restoration outcomes; (iv) offer critical challenges, gaps in knowledge, and future lines of research. It is hoped that this review will contribute to the development of a trans-disciplinary approach that can be used to design resilient ecosystems capable of supporting the ecological process and human well-being as global change accelerates [3,19,20].

2. Conceptual Framework of Engineering Resilience in Ecosystems

2.1. Evolution of Resilience Concepts across Disciplines

The idea of resilience has existed across a variety of disciplinary traditions, and each has focused on different properties of the system as well as analytical priorities. Resilience in ecology has become a concept that is used to describe the response of the ecosystem to disturbances without necessarily leading to a fundamental change in the structure or functioning of the ecosystem. This view focuses on the fact that there are various stability domains, nonlinear dynamics, and critical thresholds beyond which the system can rearrange to achieve other states. Ecological resilience, therefore, is concerned with persistence and transformation of the system in the long term as opposed to immediate restoration to balance [21].

Conversely, engineering resilience has its roots in fields that deal with the reliability and performance of systems, including structural, mechanical, and infrastructure engineering. It is typically described as the ability of a system to withstand an interruption and come back to a set functional state within a reasonable period of time. This interpretation puts a higher value on resistance, recovery rate, and efficiency, usually on the assumptions of known system behavior and a limited amount of knowledge on uncertainty. Although the assumptions seem to be limiting in ecological terms, they serve as a useful basis to quantify system performance as well as design decisions [22].

The increased appreciation of the fact that ecosystems are adaptively complex and performance-constrained has driven the trend towards efforts to combine ecological and engineering views. In place of considering these frameworks mutually exclusive, modern resilience theory is viewing them as complementary framework. The concept of engineering resilience adds a quantitative rigor, design thinking, and operational metrics to ecological resilience and insight into the adaptability of the system, diversity, and long-term sustainability. All of them are the foundation of a theoretical framework that can be used to restore dynamic environmental ecosystems in a resilient manner.

2.2. Defining Engineering Resilience in Ecological Contexts

Engineering resilience has applications to ecosystems beyond recovery to the state of equilibrium and includes the ability of ecological systems to continue functioning despite disturbance. This involves the rate of recovery as well as conservation of vital processes like the nutrient cycle, energy, and species interaction. Engineering resilience in the restoration context, then, focuses more on functional performance as opposed to adherence to the historical reference conditions. As summarized in **Table 1**, the key differences between ecological and engineering resilience offer distinct advantages for ecosystem restoration, particularly when assessing disturbance responses and system adaptability [3,23].

Table 1. Comparative definitions of resilience concepts relevant to ecosystem restoration.

Dimension	Engineering Resilience	Ecological Resilience	Socio-Ecological Resilience	Practical Implication for Restoration Design
Core focus	Performance under disturbance; recovery to target function	Persistence of function/structure across regimes; thresholds	System capacity to adapt/transform with human feedbacks	Choose goals as functional performance and learning capacity, not only reference states
Typical system model	Near-equilibrium, performance curves, reliability	Nonlinear dynamics, multiple stable states	Coupled human–natural feedbacks, institutions	Combine performance metrics with threshold awareness and governance realities
Primary disturbance lens	Disturbance as load; recovery time and service loss	Disturbance as driver of reorganization	Disturbance shaped by risk, policy, behavior	Embed disturbance regimes into design scenarios and policy constraints

Table 1. *Cont.*

Dimension	Engineering Resilience	Ecological Resilience	Socio-Ecological Resilience	Practical Implication for Restoration Design
Key properties	Resistance, recovery rate, robustness, redundancy	Diversity, connectivity, adaptive reorganization	Adaptive governance, equity, agency	Balance redundancy and diversity with institutional capacity to adapt
Failure mode	Not meeting performance thresholds	Regime shift to alternative state	Maladaptive lock-in, inequitable outcomes	Include early-warning indicators and flexibility to avoid lock-in
Success criterion	Service/function maintained and rapidly restored	System remains within desired regime	System sustains function and legitimacy over time	Evaluate both biophysical outcomes and social durability

One of the main characteristics of engineering resilience in ecosystems is the explicit consideration of the disturbance regimes. Instead of managing disturbances as exceptions, this framework views disturbances as normal constituents of the ecological processes. Engineering resilience aims at designing restoration actions that predict the occurrence and intensity of disturbances with their spatial distribution in order to increase system strength and minimize vulnerability. This strategy is in line with the developing opinions that success in restoration must be gauged on system performance during stress and not stability during optimal conditions [24].

Notably, ecological resilience engineering does not mean strict regulation and simplification. Indeed, it commonly depends on the complexity in ecology, including species diversity, functional redundancy, and spatial heterogeneity, to increase the system's robustness. The engineering design principles are then used in a manner that serves to promote and not to inhibit natural adaptive processes. This is the tension between deliberate design and ecologically-based self-organization and might be seen as the main challenge and opportunity of resilience-based restoration.

2.3. Dimensions of Engineering Resilience

The concept of engineering resilience in ecosystems can be visualized on many inseparable dimensions that combine as a unit to define the performance of the system under disturbance. Resistance is a property of a system that allows it to withstand perturbations without degrading its functionality. Due to ecological factors, resistance can be affected by species characteristics, habitat structure, and availability of resources. Recovery is a way of describing how fast and in what direction system functions are restored after being disturbed, and it is a feature of both biophysical and management treatments [25].

Adaptability is a third dimension of engineering resilience that is becoming more and more important. Adaptability demonstrates the ability of ecosystems to change in structure and operation due to a change in circumstances and thus remain viable in the long term. This aspect is especially important when considering climate change as a case where the future environmental conditions could be significantly different compared to the past. Engineering-wise, flexibility can be facilitated in terms of the modular designs, flexible management styles, and feedback systems that allow learning and adaptation as time progresses.

These dimensions do not work independently but interact in intricate ways. Highly-resistant systems can be slower in the recovery process when perturbations are stronger than the design values, though moderately-resistant but highly-adaptive systems can be better in the long run. To develop stable and resilient restoration interventions, it is important to note the existence of these trade-offs.

2.4. Metrics and Assessment of Ecosystem Engineering Resilience

The measurement of engineering resilience in ecosystems is a methodological issue because of the complexity of the system and the lack of data [26]. However, there has been an advancement in the development of metrics to reflect important elements of system performance. One of the common measurements of resilience after disturbance events is recovery time, the quantity of ecosystem services returning to normal, and the deviation of the baseline functional indicators. These measures allow comparative analysis of the restoration plans and influence the adaptation management. As shown in **Table 2**, operationalizing engineering resilience in ecosystem restoration requires selecting appropriate metrics for resistance, recovery, adaptability, and other resilience dimensions [9,27].

Table 2. Operationalizing engineering resilience in ecosystem restoration.

Resilience Dimension	What It Represents in Restoration	Example Measurable Indicators	Typical Data Sources	Common Pitfalls	Recommended Practice
Resistance	Degree of functional loss during disturbance	Peak service loss; % canopy mortality; turbidity spike; erosion rate	Field sensors, post-event surveys, remote sensing	Measuring only structure, not function	Tie indicators to services and disturbance type (flood, drought, fire, heat)
Recovery	Speed and pathway of functional return	Time-to-threshold recovery; recovery slope; service restoration rate	Time-series monitoring, satellite time stacks	Short monitoring windows miss delayed failures	Use multi-year trajectories and post-event sampling windows
Robustness	Ability to maintain performance across variability	Performance variance under variable forcing; failure probability	Models + monitoring, stress tests	Overfitting designs to mean conditions	Evaluate under extreme-event scenarios and uncertainty bounds
Redundancy	Backup capacity if components fail	Functional overlap among species/patches; network connectivity indices	Trait databases, landscape metrics	Redundancy mistaken for "more of the same"	Promote functional diversity and spatially distributed components
Adaptability	Capacity to adjust under change	Directional shifts in composition while maintaining function; adaptive management response time	Long-term monitoring, governance logs	Interpreting change as failure	Define acceptable change envelopes ("safe-to-fail" trajectories)
Transformability	Ability to shift to new desirable regime	Achievement of new stable functioning under novel climate	Scenario modeling, longitudinal evidence	Lack of social acceptance	Co-define targets with stakeholders; document trade-offs

A functional indicator is also useful in resiliency analysis since it connects ecological processes with ecological services and management goals. As an illustration, proxies of system functionality can be primary productivity, water purification capacity or flood attenuation performance. The level of monitoring technologies and data analytics has improved the viability of monitoring these indicators on appropriate spatial and temporal scales[28].

Regardless of these developments, there is no single universally accepted measure of resilience, which has echoed the situation of situational aspects about ecosystems and restoration ambitions. A pluralistic approach that involves the incorporation of quantitative indicators and qualitative system knowledge is therefore beneficial in engineering resilience assessment. These integrative tests are useful in making better decisions during design and enhancing the ability to predict system behavior during future disturbance conditions.

2.5. Engineering Resilience in Coupled Human–Natural Systems

The restoration of the ecosystem is gaining momentum in the landscapes that have been influenced by the processes of human activity, governmental structures, and socioeconomic limitations. Consequently, the concept of engineering resilience has to be viewed in the wider scope of the coupled human and natural systems. The ecological resilience can be either strengthened or weakened by human interventions based on their interaction with natural processes and feedbacks[29].

The concept of engineering resilience offers a systemic solution in the integration of both social and ecological aspects, in that restoration systems are considered multifunctional designs. These designs will be intended to provide ecological advantages and also address human demands, including the reduction of risks, the provision of resources, and cultural values. Adaptive governance, involvement of stakeholders, and alignment of policies are thus considered as inseparable elements of resilience-oriented restoration. Resilience-based approaches recognize the existence of anthropogenic power by inculcating ecological systems in engineered and social infrastructures with the aim of improving ecological integrity. The integrative approach is the key to attaining lasting restoration results in the period of rapid environmental change and human evolution[30].

3. Novel Engineering-Based Approaches in Ecosystem Restoration

3.1. Nature-Based Solutions and Hybrid Engineering Designs

The nature-based solutions have become the key paradigm in the development of system restoration approaches based on resilience, which is where natural processes are utilized to overcome environmental issues to transform them into ecological, social, and economic advantages. Engineer-wise, these solutions are being more and more formulated in terms of a functional system performance which is designable, modelable, and optimizable. They can be in the form of restored floodplains to smooth out peak flows, vegetated shoreline to lessen energy in waves and urban green space to moderate microclimates. The nature-based solutions are in line with the engineering resilience principles by explicitly connecting the ecosystem structure to quantifiable performance outcomes [31].

As a matter of fact, numerous restorations work currently assume hybrid designs which incorporate ecological elements together with the traditional engineered designs. These gray-green systems aim to exploit the advantages of both methods to make them stronger and at the same time more flexible and adaptable. As an example, living shoreline can be combined with submerged breakwaters in coastal protection plans to facilitate short-term reduction in risks and ecological growth in the long term. The hybrid systems are especially useful in high-risk or densely populated locations where interventions that are entirely nature-based might not be initially able to meet the performance requirements. The difficulty is to develop these systems in ways that do not simplify ecologies but rather enhance the dynamism of the ecosystem with engineered components as facilitating it [32–34].

3.2. Ecological Engineering and System-Level Design

Ecological engineering is a paradigm in the application of engineering resilience concepts on the restoration of ecosystems. It entails the conscious planning of ecosystems that combine the human society with the natural environment to the advantage of both. In contrast to traditional engineering, ecological engineering is a field that works under uncertain and self-organizing conditions and designs that can adapt to variability need to be made, not dictated [35].

Ecological engineering is characterized by system-level design. Concepts of restoration interventions. Grasping of restoration interventions is among a wide panorama of elements that are seen as relating to each other in a larger landscape matrix with local activities that have an impact on regional processes, including hydrology, nutrient flows, and species dispersal. Redundancy, spatial heterogeneity, and modularity in the design of a system will improve engineering resilience. Such properties enable the localized failure to be spread without spreading effects, which enhances the stability of the whole system and recovery capability [36].

The recent development in the field of landscape-scale planning and ecosystem modeling has enhanced the ability to apply system-level designs. Through simulating disturbance events and recovery paths, designers have the opportunity to compare various settings and discover the strategies to optimize resilience in both space and time. These methods change the restoration practice to the proactive, design-based solutions instead of reactive interventions.

3.3. Digital Technologies for Resilience Assessment and Optimization

With the incorporation of digital technologies, the range of tools to be used in the restoration of the ecosystem based on the concept of resilience has greatly increased. Satellite images and unmanned aerial systems are remote sensing platforms that contain high-resolution information about ecosystem structure, functioning, and processes of change with time. These data allow for constant tracking of restoration results and early observing stress indicators, which allow in time to respond to the management of stress.

Internet-of-Things technologies and environmental sensors also allow real-time monitoring of the main variables, including soil moisture, water quality, and microclimatic conditions. Combined with data assimilation and modeling frameworks, such observations help create digital representations of ecosystems, which can be utilized in testing design assumptions as well as predicting system behavior in future disturbances. These digital twins can provide an effective vehicle for experimenting with resilience trade-offs and optimization of restoration approaches before action [35].

The methods of machine learning and artificial intelligence are being used to analyze various ecological information that is complex and high-dimensional ecological information. These are tools that facilitate the identification of nonlinear relationships, thresholds, and emerging patterns that cannot be easily identified by the conventional methods of statistics. Digital technologies help to enhance the predictive capacity, which leads to a more anticipatory and adaptive type of ecosystem restoration in line with the engineering resilience principles[37].

3.4. Adaptive Management and Feedback-Control Strategies

Engineering resilience is heavily based on adaptive management, which relies on learning and adaptability by reacting to the feedback of the system. Adaptive management frameworks applied in the restoration of ecosystems acknowledge that there is always uncertainty and that the design of the restoration will change over time as new information is released. Adaptive management would be enhanced with the introduction of engineering resilience that adds the formal concepts of control that connect monitoring data to management action.

The feedback-control strategies also allow the restoration systems to react dynamically to changes in the environment. An example is that to achieve the functional performance of wetlands, variable hydrological manipulations can be used to manage the water levels to respond to seasonal changes or extreme conditions. Equally, real-time warnings of ecosystem stress or recovery can be used as adaptive vegetation management. Such strategies make restoration not one-time but a process of system tuning and optimization[38–40].

The success of adaptive management is based on the choice of proper indicators, specific performance levels, and the capability of the institution to make decisions. Resilience engineering brings systematic approaches to the definition of such aspects, enhancing clarity and responsibility in the restoration practice. **Table 3** offers a summary of engineering-based restoration approaches and the mechanisms they utilize to enhance resilience, such as modularity, redundancy, and process restoration[41–43].

Table 3. Novel engineering-based restoration approaches and their resilience mechanisms.

Approach Category	Representative Interventions	Primary Resilience Mechanisms	Best-Fit Ecosystems	Key Enabling Requirements	Risks/Limitations
Nature-based solutions	Floodplain reconnection, living shorelines, urban forests	Dissipation, buffering, self-repair	Rivers, coasts, cities	Space allocation, long-term stewardship	Slow maturation; uncertain performance under extremes
Hybrid gray–green systems	Breakwaters + reefs; levees + wetlands	Immediate robustness + long-term ecological reinforcement	Coasts, deltas, urban coasts	Integrated design standards, permitting	Ecological lock-in; maintenance burden
Ecological engineering	Constructed wetlands, engineered successional mosaics	Redundancy, modularity, process restoration	Freshwater, agricultural landscapes	Systems modeling; process-based monitoring	Oversimplification if designs are too prescriptive
Digital monitoring & analytics	Remote sensing, sensor networks, AI early warning	Early detection, adaptive response, improved prediction	All, especially large-scale	Data pipelines, QA/QC, governance for action	Data-rich but decision-poor implementations
Control-inspired adaptive management	Rule curves for water levels; dynamic grazing/fire regimes	Feedback control, learning loops, recovery acceleration	Wetlands, rangelands, fire-prone systems	Clear thresholds, authority to adjust	Institutional inertia; unclear accountability
Emerging bio/material innovations	Biodegradable structures; assisted adaptation	Enhanced establishment, stress tolerance	Coasts, degraded soils	Ethical review, long-term monitoring	Unintended ecological effects; acceptance barriers

3.5. Emerging Biotechnological Interventions: Opportunities and Risks

Biotechnological approaches, including assisted evolution and selective breeding, offer potential to enhance ecosystem resilience under rapid environmental change. However, their application raises significant ecological and ethical concerns. Targeted trait selection may reduce genetic diversity, potentially limiting long-term adaptive capacity. Introduced or modified organisms may also generate unintended effects on non-target species through altered ecological interactions or gene flow.

The potential irreversibility of such interventions presents an additional challenge, particularly in open ecosystems where containment is difficult. Moreover, long-term monitoring of evolutionary and ecological outcomes remains limited, increasing uncertainty regarding unintended consequences.

Current regulatory frameworks are often insufficient to address interventions at genetic and evolutionary scales, and ethical considerations—including ecological integrity and stakeholder acceptance—remain underdeveloped. Accordingly, a precautionary approach is required. This includes prioritizing controlled, small-scale trials, implementing robust monitoring systems, and establishing adaptive governance structures.

While biotechnological interventions may complement restoration strategies, their application should be carefully constrained and guided by rigorous risk assessment, transparency, and long-term ecological safeguards[44,45].

4. Applications, Case Studies, and Challenges

4.1. Cross-Ecosystem Applications of Resilience-Oriented Restoration

The operationalization of engineering resilience has been done over a very broad range of ecosystem types, as well as indicating the universal dynamics of disturbance and the specificity of restoration goals. In terrestrial ecosystems, fire regime management, drought stress, soil degradation and invasive species pressures are frequently considered as the focus of restoration through resilience. The interventions are progressively aimed at reinforcing process integrity (through hydrological control, nutrient cycling, etc.), but not merely at recreating assemblages of species of the past. Catchment scale planning, river reconnection, and redesigning flow regimes are often grounded in resilience-oriented approaches in freshwater systems to promote ecological processes at altered hydrological and climate variability conditions[46].

Coastal and marine environments provide particularly conspicuous settings to take advantage of engineering resilience due to the high-energy perturbations that they face, as well as the close interconnection to human infrastructure. Examples of interventions that directly relate ecological structure with performance outcomes of protective functions (reduced wave energy and erosion) include living shorelines, reconstructions of dunes, oyster-reef installations and mangrove restoration. Resilience-based restoration in urban ecosystems can quickly become linked to engineered systems since the city environment is largely characterized by altered hydrology, fragmented habitats, and heat and pollution stressors. In this case, restoration is oftentimes affected by means of multifunctional green infrastructure, which is meant to achieve ecosystem services, such as regulation of stormwater, heat, and biodiversity support, subject to design and maintenance limitations. **Table 4** provides a comparative overview of ecosystem-specific applications of resilience-based restoration, highlighting typical disturbances, resilience goals, and common challenges in implementation[47,48].

Table 4. Ecosystem-specific applications, disturbance regimes, and challenges in resilience-based restoration.

Ecosystem Context	Dominant Disturbances	Typical Resilience Goals	Suitable Approaches (from Section 3)	Evaluation Emphasis	Recurring Challenges
Terrestrial (forests, rangelands)	Drought, fire, invasives, heat	Maintain productivity, habitat function, post-fire recovery	Ecological engineering; adaptive management; monitoring/AI	Recovery trajectories; compositional change within acceptable bounds	Competing land uses; long successional timescales
Freshwater (rivers, wetlands, lakes)	Floods, flow alteration, nutrient loading	Water quality, habitat connectivity, flood attenuation	Nature-based; system-level design; control-inspired operations	Functional indicators (nutrients, turbidity), connectivity metrics	Upstream drivers, governance fragmentation
Coastal/marine (shorelines, reefs, estuaries)	Storm surge, sea-level rise, erosion	Risk reduction + habitat persistence	Hybrid gray–green; living shorelines; materials innovations	Performance under extremes; shoreline change rates	Permitting, uncertainty in extreme-event performance

Table 4. *Cont.*

Ecosystem Context	Dominant Disturbances	Typical Resilience Goals	Suitable Approaches (from Section 3)	Evaluation Emphasis	Recurring Challenges
Urban ecosystems	Heat, runoff extremes, pollution, fragmentation	Service reliability (cooling, stormwater, equity)	Green infrastructure networks; digital twins; hybrid designs	Reliability, maintenance performance, service distribution	Maintenance funding, equity impacts, space constraints
Agricultural mosaics	Soil loss, drought, chemical stress	Soil function, nutrient retention, connectivity	Ecological engineering; nature-based buffers	Soil metrics; service trade-offs	Adoption incentives, policy alignment

In these environments, a fundamental change has been made: restoration projects are becoming assessed by the level to which they preserve functionality and services during disturbance, as opposed to their similarity to a reference state pre-disturbance. This change is consistent with the performance, reliability, and recovery paths focus of engineering resilience, and specifically so in a climate nonstationary in which past baselines might not be viable objectives.

4.2. Evidence from Case Studies and Lessons on Performance

Case studies have the benefit of offering important information on how engineering resilience can be translated into restoration practice, especially when they are accompanied by clear performance goals, monitoring data, and a direct consideration of disturbance regimes. Projects in the field of coastal restoration that incorporate biological elements in engineered construction are often more robust in the initial years, during which engineered natural elements may not have the strength to perform the protective role. However, with time, the ecological elements may be more effective because habitats become more mature, which may eliminate the need to use hard infrastructure. These paths describe a key benefit of resilience-based designs, i.e., they may confer short-term stability, whilst allowing long-term ecological self-reinforcement[49].

In river and floodplain restoration, resilience-based designs tend to focus on reconnecting and space of hydrologic processes, enabling systems to dissipate energy and recover after floods. Recovery capacity can be increased by the application of projects that can restore lateral connectivity, and sediment processes that allow habitat to regenerate and remain complex geomorphologically. But these undertakings also expose a similar problem; results are highly contingent on upstream management, land-use processes, and governance choices that transcend the area of restoration. Resilience engineering can therefore not be considered as a local property, but an emerging feature which is influenced by regional forces.

Cases in restoration of the urban setting are often cited as demonstrating the importance of redundancy and distributed design. Green infrastructure networks (bioswales, constructed wetlands, permeable surfaces, and urban forests) can also offer resilience in case one or more parts of the network malfunction or perform poorly. It is also through these systems that the significance of maintenance and institutional capacity can be seen as determinants of long-term performance. In contrast to most non-urban restorations, urban resilience is frequently conditional upon unceasing human intervention and makes the concept of self-sufficient ecosystems difficult, necessitating an explicit consideration of operational limitations.

Although case studies usually record favorable results, they also highlight that resilience is not equal to general improvement. Increasing system resistance can slow responsiveness or limit ecological processes, or prioritizing adaptability can permit species changes that disrupt stakeholder anticipations. Most informative cases, therefore, are the ones that explicitly describe trade-offs and report on system behavior over time, and do not only use post-intervention indicators in the short-term[39].

4.3. Scaling, Transferability, and Long-Term Durability

Moving resilience-oriented restoration between pilot projects to the landscape or regional levels is a frontier. Most of the interventions involving engineering would work effectively in a controlled or well-financed environment and experience limitations when applied to heterogeneous environments with different governing capacities. The limitation on transferability arises when the designs are viewed as templates and not as context-specific solutions based on the local disturbance regimes, ecological processes, and socio-economic conditions[50].

Durability in the long-term is especially problematic due to lagging features of the restoration systems and subsequent slow failures that are not recorded by short monitoring windows. Ecosystems can be balanced in the initial post-restoration times only to become susceptible as the climate pressures, frequency of disturbance, and maintenance diminish. Engineering resilience emphasizes the importance of considering the results of restoration over time scales that are in harmony with ecological processes, such as successional patterns and processes that change slowly, such as soil formation and groundwater interactions.

Whether success is achieved on a large scale is also a tricky question. Mega restoration can be associated with large-scale restoration mosaics that have various aims and limitations. It has been proposed that the success of individual sites should not be judged in isolation but by the stability and recovery ability of a system overall, using a resilience-based framework. This would suggest that it requires network-based assessment, spatial planning strategies, and integrated forms of governance that are capable of bringing various projects into common resilience objectives[51–53].

4.4. Socio-Economic, Governance, and Policy Constraints

Since restoration is an activity operating within a coupled human-natural system, socio-economic and governance processes often dictate the extent to which engineering resilience can be used in a meaningful way. The funding structures tend to support the short-term deliverables over the long-term performance, which can encourage the restoration designs that encourage immediate visible effects compared to those that are sustainable against disturbance. Likewise, the regulatory regimes can be characterized by focusing on correspondence with historical standards or strict definitions of habitats and restricting the adaptiveness of adaptive, resilience-focused responses.

Resilience goals may also be defined by the stakeholder values in a way that causes tension between ecological dynamics and social expectations. Communities can adopt a focus on the short-term risk mitigation, aesthetic values, or particular species outcomes, whereas resilience-oriented designs can involve ecological tolerance and risk acceptance. To facilitate these negotiations, the approach of engineering resilience can help by ensuring that trade-offs are made clear and that restoration objectives are defined in terms of performance during disturbance. This, however, needs transparency in the way performance is determined, beneficiaries, and what risks are being addressed[54].

Urban and coastal environments are particularly likely areas where equity impacts influence municipal restorations, which could overlap with land values, access to ecosystem services, and displacement pressures. The resilience-based restoration may unintentionally serve the needs of the well-resourced communities and transfer risks to others. Consequently, equity, participation, and accountability forms of governance are critical elements of resilient restoration planning[55].

4.5. Technical Limitations, Trade-Offs, and Unintended Consequences

When founded on engineering, the technical challenges present engineering-based approaches to restoration become underestimated in traditional discourses of restoration. Resilience designs involve assumptions concerning regimes of disturbance in the future, which are becoming more unpredictable due to climate change. In the case of overconfidence in predictive models, the resulting designs might be very effective in the way they are supposed to be, but in the case of extreme or new circumstances. This supports the value of safety margins, redundancy, and adaptive capacity, instead of using optimization to a limited set of conditions.

Resilience-based design is a type of trade-off. The ensuing lowering of resistance via structural reinforcement can decrease habitat dynamics or limit successional dynamics. This could involve accommodating intermittent disruption and partial system restructuring that can be politically or socially controversial. Furthermore, ecological spillovers, including the change in the transportation of sediments, nutrient cycles, or specific species distributions, could be caused by resilience interventions outside of the project. Such spillovers can be positive or negative, but they highlight the significance of analysis at the system level and the learning after the implementation[56].

New technologies may also have unwanted effects. Indicatively, biotechnological interventions that help enhance stress tolerance may influence genetic diversity, interactions between species, or evolutionary pathways in a manner that is hard to predict. Equally, the hybrid gray-green systems can trap the landscapes into specific forms that lack long-term flexibility when the engineered elements are obstacles to the natural reorganization. They are not risks that oppose innovation but emphasize the importance of stringent evaluation systems, ethical interrogation, and governance systems, which can respond to the emergent evidence.

4.6. Knowledge Gaps and Research Priorities for Resilient Restoration

The conceptual and methodological gaps that exist limit the use of engineering resilience to restore ecosystems. A consistent issue is that there are no standardized metrics that can be used across a variety of ecosystems but that are sensitive to context. Without regular evaluation systems, restoration strategies cannot be compared, generalization cannot be performed, and evidence-based policy cannot be supported. The innovations in monitoring technologies have potential, but they should be combined with the conceptual models that help to understand what has to be measured, during what time periods, and for what types of decisions.

The second main gap is associated with the translation of the resilience theory into practical design principles. Although terms such as redundancy, modularity, and adaptive capacity are commonly appealed to, their practical application in an ecological system needs to be better guided and empirically justified. This involves learning about the role of biodiversity and functional diversity in ecosystem resilience in various contexts and how interventions by engineers can be used to enhance these attributes without simplifying the workings of an ecosystem[27,57,58].

Lastly, there are still a few long-term studies, especially ones that test the response of the system to actual disturbances as opposed to what is simulated. By the fact that resilience is essentially unveiled in times of strain, the empirical information of disturbance events, drought, floods, storms, heatwave and biological invasions is essential in verifying design assumptions, as well as enhancing future interventions. To assemble evidence of this magnitude will demand a quidian commitment of funding, globalized monitoring systems, open data policy, and interdisciplinary efforts by the ecology disciplines, engineers, and social scientists.

5. Conclusion and Future Perspectives

5.1. Engineering Resilience and Restoration

The timely and ever more fixed framework of engineering resilience provides an ecosystem restoration tool that is both urgently needed and increasingly relevant in the era of climate nonstationary, growing disturbance regimes, and further human pressure. Throughout the conceptual underpinnings of the discussion in Section 2 and the new approaches and applications in Sections 3 and 4, there is a major theme in that restoration can no longer be measured primarily in reference to unchanging reference conditions. Rather, restoration success is increasingly characterized by the ability of ecosystems to remain operational, to recover successfully, and to adjust to environmental changes, and yet still be able to offer biodiversity sustenance and ecosystem services.

The change does not override ecological resilience theory but complements it and operationalizes it through a design-oriented lens. Resilience engineering adds feasible stress to performance targets, quantifiable metrics, system dependability, and optimization by trial and error. When such factors are combined with ecological understanding of thresholds, self-organization, diversity, and long-term system dynamics, the practice of restoration would be in a better position to tackle the uncertainty and disturbance as inherent aspects rather than external interruptions. Strongest restoration plans are hence those plans that do not rely on the concept of resilience as a desirable quality, but instead, the design parameter based on the principles of monitoring, modelling, and adaptive governance[20,49].

5.2. Implications for Restoration Design, Monitoring, and Decision-Making

A resilience-based approach implies that the planning of restoration needs to start with clear definitions of functional performance during disturbances. This demands the expression of priorities of which ecosystem functions and services should be prioritized, the levels of degradation that are tolerated in times of disturbance, and the recovery paths that form success. These definitions can help to clarify the trade-offs and facilitate clear negotiation between the stakeholders, especially when social priorities vary among communities, sectors, and levels of governance[59]. To navigate uncertainties in restoration design, **Figure 2** offers a stepwise decision framework for selecting and adapting resilience-based restoration strategies over time.

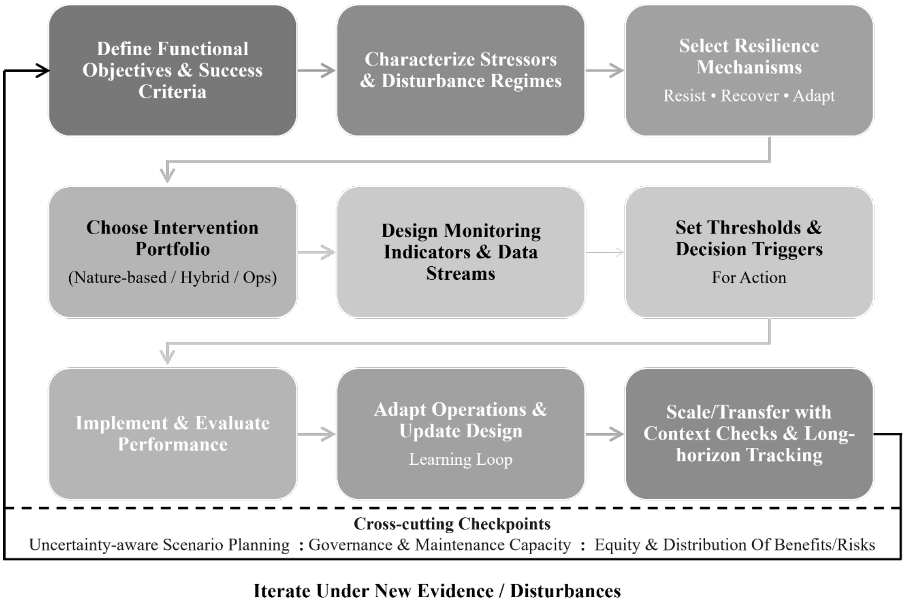

Figure 2. Decision framework for resilience-oriented restoration under uncertainty.

The practicality of engineering resilience promotes the establishment of restoration designs with redundancy, modularity, and heterogeneity, which decreases the chances of localized failures to cause system-wide collapse. It also encourages a broader role of monitoring as a decision-support process as opposed to a post-hoc assessment instrument. Monitoring can be used to offer near real-time signs of ecosystem stress and recovery as sensor networks, remote sensing platforms, and data analytics are increasingly available, which can then be responded to in adaptive management more rapidly, targeted, and effectively.

Nevertheless, institutional capacity is also needed in the adoption of resilience-based decision-making. Adaptive management has been touted and is not distributed evenly because of limitations in the availability of funds, power, technical knowledge, and agency coordination. The concept of engineering resilience supports the notion that restoration is not an ecological intervention, but a long-term commitment to the operation, particularly in the landscapes that are greatly modified. This capacity will be as relevant as technical design improvement, especially where long-term maintenance and continuity of governance are required to attain long-lasting results[60].

5.3. Toward Standardized Metrics and Comparable Evidence

The problem of standardized metrics that can be transferred is one of the most unrelenting impediments to engineering resilience in ecosystem restoration. Although resilience is context-specific in nature, it is possible to move forward by creating metric families that can be customized to ecosystem type and management goals and still have fundamental comparability. The disturbance response, functional degradation, recovery rates, and longer-term responsiveness, as such measures, should be registered, and these measures need to be directly associated with ecosystem services and biodiversity results[11].

Comparability is also reliant on the uniformity of time periods of observation in line with ecological processes. Short appraisal periods can overvalue success because they can be established at early stages of establishment before significant disturbances can take place, but longer appraisals can identify delayed failures or trade-offs, which only become apparent during stress. Developing strong evidence will thus demand long-term surveillance schemes, common protocols, and open data infrastructures into which synthesis across areas and ecosystems can be performed. In the absence of the investments, the aspect of resilience will continue to be hard to measure and hard to generalize to anything other than individual cases.

5.4. Designing Restoration under Deep Uncertainty

Ecosystem restoration increasingly operates under deep uncertainty, where future disturbance regimes and system responses cannot be reliably predicted. In this context, resilience-oriented design should prioritize robustness across multiple plausible futures rather than optimization for a single trajectory. Scenario planning enables evaluation of restoration performance under contrasting disturbance and climate conditions, supporting strategies that remain effective under uncertainty.

Adaptive pathways further enhance resilience by structuring interventions as flexible, staged actions linked to monitoring thresholds. This allows restoration designs to be adjusted over time, reducing the risk of maladaptive lock-in. In parallel, safe-to-fail experimental approaches support iterative learning by testing interventions at scales where failure does not compromise system integrity.

These approaches align with decision-science frameworks such as robust decision-making and dynamic adaptive policy pathways, which emphasize flexibility, learning, and performance under uncertainty. Integrating these principles strengthens the capacity of restoration systems to remain functional and adaptable under nonstationary environmental conditions[61–63].

5.5. Research Priorities and Future Directions

There are a number of research priorities that appear to be of critical importance to engineering resilience in ecosystem restoration. To begin with, there is a necessity to further incorporate ecological theory and engineering practices to use the abstract concepts of resilience into practical design principles. These involve explaining how redundancy, diversity, connectivity, and modularity may be transparently done on various ecosystem types and disturbance regimes, and how this interacts with the engineered parts over time.

Second, prediction ability should be enhanced without exaggerating confidence. This demands models that bring in explicit facing of uncertainty, nondynamic behavior, and extreme event behavior, and validation of such models by real-life disturbances. Planning that involves the exploration of a variety of possible futures by use of scenario-based planning methods would be more effective than single best estimate projections, especially when climate-driven risks are changing quickly.

Third, the resilience-based restoration will mandate further emphasis on the landscape connectivity and cross-boundary governance. The drivers that determine the outcomes of restoration efforts go beyond the extent of the project environment to include upstream land use, regional hydrology, and policy incentives. Research and practice should then shift to the networked design and multi-project planning frameworks, which consider the system interactions, cascading risks, and accumulating benefits.

Lastly, interdisciplinary cooperation should be maintained for the future of resilient restoration. Ecological restoration involving the incorporation of engineering resilience is not merely a technological change but a change in methodologies and institutions. The next steps can only be achieved through the common language, combined training opportunities, and collective platforms that will be able to bridge ecologists, engineers, social scientists, policymakers, and the local stakeholders. This kind of integration can facilitate restoration approaches that will not only be effective in the current conditions, but that will be strong and flexible in the future uncertainties.

There is a shift in the direction in which ecosystem restoration is moving into a phase where historical baselines are becoming more unpredictable, and disturbance regimes are becoming more intense. Engineering resilience offers a practical approach to addressing this fact with the focus on functional performance, recovery paths, flexibility, and learning through trial and error. Resilience-oriented restoration can redirect practice by reconstructing fragility into long-lasting system design by thoughtfully incorporating the principles of ecological resilience, based on the principles of inclusive governance and long-term evidence. The task to come is not to recover ecosystems, but in fact to design a situation where ecosystems can survive, restructure, and keep sustaining life and human well-being in an evolving world.

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References

[1] Philp, R.B., 2012. Environmental Issues for the Twenty-First Century and Their Impact on Human Health. Bentham Science Publishers: Sharjah, United Arab Emirates.
[2] Drotianko, L., Sydorenko, S., Kleshnia, H., et al., 2022. New Environmental Challenges of the 21st Century. In Lecture Notes in Networks and Systems. Springer: Cham, Switzerland.
[3] Ren, J.W.F., Coffman, G.C., 2023. Integrating the resilience concept into ecosystem restoration. Restoration Ecology. 31(5), e13907.
[4] Collier, M.J., 2015. Novel ecosystems and social-ecological resilience. Landscape Ecology. 30(8), 1363–1369.
[5] Abhilash, P.C., 2021. Restoring the unrestored: Strategies for restoring global land during the UN decade on ecosystem restoration (UN-DER). Land. 10(2), 201.
[6] Linkov, I., Trump, B.D., 2019. The Science and Practice of Resilience. Springer: Cham, Switzerland.
[7] Tullos, D., Baker, D.W., Curran, J.C., et al., 2021. Enhancing resilience of river restoration design in systems undergoing change. Journal of Hydraulic Engineering. 147(3), 03121001.
[8] Timpane-Padgham, B.L., Beechie, T., Klinger, T., 2017. A systematic review of ecological attributes that confer resilience to climate change in environmental restoration. PLoS One. 12(3), e0173812.
[9] Chambers, J.C., Allen, C.R., Cushman, S.A., 2019. Operationalizing ecological resilience concepts for managing species and ecosystems at risk. Frontiers in Ecology and Evolution. 7, 241.
[10] Eriksson, O., 2021. The importance of traditional agricultural landscapes for preventing species extinctions. Biodiversity and Conservation. 30(5), 1341–1357.
[11] Mitsch, W.J., Jørgensen, S.E., 2003. Ecological Engineering and Ecosystem Restoration. John Wiley & Sons: Hoboken, NJ, USA.
[12] Krievins, K., Plummer, R., Baird, J., 2018. Building resilience in ecological restoration processes: A social-ecological perspective. Ecological Restoration. 36(3), 195–207.
[13] Holling, C.S., 1996. Engineering resilience versus ecological resilience. Engineering within Ecological Constraints. 31, 32.
[14] Waryszak, P., Gavoille, A., Whitt, A.A., et al., 2021. Combining gray and green infrastructure to improve coastal resilience: Lessons learnt from hybrid flood defenses. Coastal Engineering Journal. 63(3), 335–350.
[15] Guo, Y., Liu, S., Dong, Y., et al., 2024. Research progress and prospects of nature-based solutions in green infrastructure: A bibliometric analysis. Ecological Frontiers. 45(3), 561–571.
[16] Das Malakar, K., Kumar, M., Anand, S., et al., 2023. Climate, climate change ecology, and socio-ecological environments. In Climate Change and Socio-Ecological Transformation: Vulnerability and Sustainability. Springer Nature Singapore: Singapore. pp. 29–116.
[17] Elsawah, S., Filatova, T., Jakeman, A.J., et al., 2020. Eight grand challenges in socio-environmental systems modeling. Socio-Environmental Systems Modelling. 2, 16226.
[18] Masarei, M.I., Erickson, T.E., Merritt, D.J., et al., 2021. Engineering restoration for the future. Ecological Engineering. 159, 106103.
[19] Miller, B.P., Sinclair, E.A., Menz, M.H.M., et al., 2017. A framework for the practical science necessary to restore sustainable, resilient, and biodiverse ecosystems. Restoration Ecology. 25(4), 605–617.
[20] Simonson, W.D., Miller, E., Jones, A., et al., 2021. Enhancing climate change resilience of ecological restoration—A framework for action. Perspectives in Ecology and Conservation. 19(3), 300–310.
[21] Ungar, M., 2018. Systemic resilience: principles and processes for a science of change in contexts of adver-

sity. Ecology and Society. 23(4), 34.

[22] Wang, X., Mazumder, R.K., Salarieh, B., et al., 2022. Machine learning for risk and resilience assessment in structural engineering: Progress and future trends. Journal of Structural Engineering. 148(8), 03122003.

[23] Lake, P.S., 2013. Resistance, resilience and restoration. Ecological Management & Restoration. 14(1), 20–24.

[24] Mori, A.S., 2011. Ecosystem management based on natural disturbances: Hierarchical context and non-equilibrium paradigm. Journal of Applied Ecology. 48(2), 280–292.

[25] Battisti, C., Poeta, G., Fanelli, G., 2016. An Introduction to Disturbance Ecology. Springer: Cham, Switzerland. pp. 13–29.

[26] Naghshbandi, S.N., Varga, L., Purvis, A., et al., 2020. A review of methods to study resilience of complex engineering and engineered systems. IEEE Access. 8, 87775–87799.

[27] Yodo, N., Wang, P., 2016. Engineering resilience quantification and system design implications: A literature survey. Journal of Mechanical Design. 138(11), 111408.

[28] Oliver, T.H., Heard, M.S., Isaac, N.J.B., et al., 2015. Biodiversity and resilience of ecosystem functions. Trends in Ecology & Evolution. 30(11), 673–684.

[29] Tedesco, A.M., López-Cubillos, S., Chazdon, R., et al., 2023. Beyond ecology: Ecosystem restoration as a process for social-ecological transformation. Trends in Ecology & Evolution. 38(7), 643–653.

[30] Chirwa, P.W., Kozanayi, W., Uisso, A.J., et al., 2024. Socio-economic factors, policy and governance systems influencing multifunctional landscapes. In Trees in a Sub-Saharan Multi-Functional Landscape: Research, Management, and Policy. Springer: Cham, Switzerland. pp. 305–327.

[31] Nelson, D.R., Bledsoe, B.P., Ferreira, S., et al., 2020. Challenges to realizing the potential of nature-based solutions. Current Opinion in Environmental Sustainability. 45, 49–55.

[32] O'Hogain, S., McCarton, L., 2018. Nature-based solutions. In A Technology Portfolio of Nature-Based Solutions: Innovations in Water Management. Springer: Cham, Switzerland. pp. 1–9.

[33] Welden, E., Chausson, A., Melanidis, M.S., 2021. Leveraging nature-based solutions for transformation: Reconnecting people and nature. People and Nature. 3(5), 966–977.

[34] Cheng, C., Li, F., 2024. Ecosystem restoration and management based on nature-based solutions in China: Research progress and representative practices. Nature-Based Solutions. 6, 100176.

[35] Wang, X., Wang, J., Wang, B., et al., 2022. The nature-based ecological engineering paradigm: Symbiosis, coupling, and coordination. Engineering. 19, 14–21.

[36] Ghazian, N., Lortie, C.J., 2024. A review of the roots of ecological engineering and its principles. Journal of Ecological Engineering. 25(1), 345–357.

[37] Hu, K., Xu, Q., Zhu, K., et al., 2026. Recent advances of artificial intelligence in aquatic bioindicators and ecological assessment. Water, Air, & Soil Pollution. 237(5), 306.

[38] Reddy, T.A., 2020. Resilience of complex adaptive systems: a pedagogical framework for engineering education and research. Journal of Engineering for Sustainable Buildings and Cities. 1(2), 021004.

[39] Park, J., Seager, T.P., Rao, P.S.C., et al., 2013. Integrating risk and resilience approaches to catastrophe management in engineering systems. Risk Analysis. 33(3), 356–367.

[40] Aslam, M.A., Abbas, M.S., Mustaqeem, M., et al., 2024. Comprehensive assessment of heavy metal contamination in soil-plant systems and health risks from wastewater-irrigated vegetables. Colloids and Surfaces C: Environmental Aspects. 2, 100044.

[41] Khan, M.N., Aslam, M.A., Bin Muhsinah, A., et al., 2023. Heavy metals in vegetables: Screening health risks of irrigation with wastewater in peri-urban areas of Bhakkar, Pakistan. Toxics. 11(5), 460.

[42] Khan, M.N., Aslam, M.A., Zada, I., et al., 2023. Statistical analysis and health risk assessment: Vegetables irrigated with wastewater in Kirri Shamozai, Pakistan. Toxics. 11(11), 899.

[43] Chang, Z., Chunni, H., Wanghua, S., 2025. Resilience of rock engineering: concept, mechanism, evaluation and enhancement. Geoenvironmental Disasters. 12(1), 21.

[44] Wu, X., Lü, Y., Zhang, J., et al., 2023. Adapting ecosystem restoration for sustainable development in a changing world. The Innovation. 4(1), 100375.

[45] Coleman, M.A., Wood, G., Filbee-Dexter, K., et al., 2020. Restore or redefine: Future trajectories for restoration. Frontiers in Marine Science. 7, 237.

[46] Newton, A.C., Cantarello, E., 2015. Restoration of forest resilience: An achievable goal? New Forests. 46(5), 645–668.

[47] Shackelford, N., Dudney, J., Stueber, M.M., et al., 2024. Measuring at all scales: Sourcing data for more flexible restoration references. Restoration Ecology. 32(8), e13541.

[48] Wu, P.P.-Y., Mengersen, K., McMahon, K., et al., 2017. Timing anthropogenic stressors to mitigate their impact on marine ecosystem resilience. Nature Communications. 8(1), 1263.

[49] Nemeth, C.P., Hollnagel, E., Dekker, S., 2009. Resilience Engineering Perspectives, Volume 2: Preparation and Restoration. Ashgate Publishing: Farnham, UK.

[50] Falk, D.A., 2017. Restoration ecology, resilience, and the axes of change. Annals of the Missouri Botanical Garden. 102(2), 201–216.

[51] Li, W., Fang, W., Hu, Y., 2025. Integrating climate resilience into sustainable land management: A strategy to combat land degradation. Land Degradation & Development. 37(7), 2835–2853.

[52] Li, Y., Pan, Z., Shen, Y., 2025. Regional integration policies and ecological resilience: A case study of urban agglomeration planning policies in China. Frontiers in Environmental Science. 13, 1636479.

[53] Wyss, R., Luthe, T., Pedoth, L., et al., 2022. Mountain resilience: A systematic literature review and paths to the future. Mountain Research and Development. 42(2), A23–A36.

[54] Nielsen, L., Faber, M.H., 2021. Impacts of sustainability and resilience research on risk governance, management and education. Sustainable and Resilient Infrastructure. 6(6), 339–384.

[55] Pandey, B., Ghosh, A., 2023. Urban ecosystem services and climate change: A dynamic interplay. Frontiers in Sustainable Cities. 5, 1281430.

[56] Hirsch, S.L., 2018. Adaptive Epistemologies: Scientific Practice and Environmental Restoration in a Changing Climate [PhD Thesis]. University of Idaho: Moscow, ID, USA.

[57] Righi, A.W., Saurin, T.A., Wachs, P., 2015. A systematic literature review of resilience engineering: Research areas and a research agenda proposal. Reliability Engineering & System Safety. 141, 142–152.

[58] Teague, W.R., 2017. Bridging the research management gap to restore ecosystem function and social resilience. In Global Soil Security. Springer: Cham, Switzerland. pp. 341–350.

[59] Cowan, E.L., Standish, R.J., Miller, B.P., et al., 2021. A framework for measuring the effects of disturbance in restoration projects. Restoration Ecology. 29(4), e13379.

[60] Rong, J., Zhou, M., Li, G., 2023. Resilience-oriented restoration strategy by offshore wind power considering risk. CSEE Journal of Power and Energy Systems. 9(6), 2052–2065.

[61] Khan, N., 2024. Unlocking innovation in crop resilience and productivity: breakthroughs in biotechnology and sustainable farming. Innovation Discovery. 1(4), 28.

[62] Lea-Smith, D.J., Hassard, F., Coulon, F., et al., 2025. Engineering biology applications for environmental solutions: potential and challenges. Nature Communications. 16(1), 3538.

[63] Brandl, E., 2025. Applied Genetics and Biotechnology in Environmental Engineering: Challenges and Opportunities in Coastal Regions. Available from: https://books.google.com.hk/books?hl=en&lr=&id=loZpEQAAQBAJ&oi=fnd&pg=PA4&dq=info:5tRGaQHbRdkJ:scholar.google.com&ots=AYc4mMzeZB&sig=X7C2Kggw8shFRRUfPvJHpnyPy9A&redir_esc=y#v=onepage&q&f=false (cited 13 December 2025).