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Article

Methodological innovation in government environmental auditing through biomechanical principles: An approach to environmental impact performance evaluation

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Abstract: Biomechanical principles have been widely applied in multiple industries in recent years, providing new perspectives for evaluating and analyzing complex systems. In this research, the feasibility of integrating biomechanical principles into government environmental performance audits to develop a new approach to environmental impact assessment is explored. By analyzing core principles in biomechanics such as mechanical equilibrium, energy conservation, and biological adaptability, it helps to propose a series of evaluation frameworks and indicators based on biomechanical principles to quantify the key factors in environmental performance audits. The research findings indicate that the application of biomechanical principles in government environmental performance audits can not only enhance the accuracy and scientific nature of the assessment but also offer strong support for environmental protection and sustainable development, highlighting the superiority of incorporating biomechanical knowledge into environmental auditing.

Keywords: biomechanical principles; government environmental performance audit; environmental impact assessment; mechanical equilibrium; energy conservation

1. Introduction

Driven by the carbon neutrality goal, government environmental audits, serving as the “policy sensors” in ecological governance, are currently undergoing a paradigm shift from compliance orientation to ecosystem adaptive management [1,2]. This transition reflects a growing recognition of the need for more flexible and responsive auditing practices that can better align with the dynamic nature of ecological systems. By moving beyond mere compliance checks, environmental audits are beginning to incorporate principles of adaptive management, which emphasize learning and adjustment in response to changing environmental conditions. The “Guidelines for Environmental and Sustainable Development Auditing” issued by the International Organization of Supreme Audit Institutions (INTOSAI) clearly states that due to the lack of systematic modeling capabilities for energy flow, traditional audit frameworks struggle to accurately capture the effectiveness of new environmental policies such as carbon trading and ecological compensation. This highlights a critical gap in current auditing practices, where the complexity of ecological interactions and energy dynamics is often oversimplified, leading to inadequate assessments of policy impacts. This limitation can essentially be attributed to the structural conflict between “mechanistic reductionism” and the biomechanical nature of ecological system media.

Mechanistic reductionism, which breaks down systems into their individual components for analysis, fails to account for the intricate interdependencies and feedback loops present in ecological systems. This disconnect can result in a misunderstanding of how policies interact with ecological processes, ultimately undermining the effectiveness of environmental governance. Recent studies have confirmed that government environmental audits have significantly enhanced the coordinated control capabilities of regional pollutants by regulating the allocation efficiency of green financial resources. However, there remain methodological limitations in evaluating the dynamic adaptability and cross-scale governance effectiveness of complex ecosystems [3,4]. This bottleneck is particularly prominent in the environmental audit practices of large river basins such as the Yangtze River Economic Belt. Due to the self-organizing characteristics of ecosystems and the nonlinear effects of energy flow, traditional audit indicators find it difficult to accurately depict the spatio-temporal coupling relationship between policy interventions and ecological responses [5,6].

Most existing studies have focused on audit system optimization or technological innovation [7,8], but there has been a lack of in-depth exploration into the biomechanical nature of environmental governance systems. Taking the ecological restoration project in the Wuliangsuhai Basin as an example, the issue of “governance elasticity threshold” existing in the implementation of ecological protection policies urgently requires theoretical breakthroughs [9]. In this study, we introduce the principle of biomechanical energy conversion to reveal the inherent laws of ecosystems at the levels of material transfer and energy dissipation: just as the strain capacity of a biological organism depends on tissue viscoelasticity, the effectiveness of government environmental audits is also constrained by the dynamic balance between “policy rigidity” and “ecological resilience”. For the first time, we propose that ecological environmental performance can be abstracted as a biomechanical cycle process consisting of “stress response-energy reorganization-system restoration” (as shown in **Figure 1**). This new perspective provides a theoretical tool for resolving the discretization dilemma of natural resource asset valuation [10].

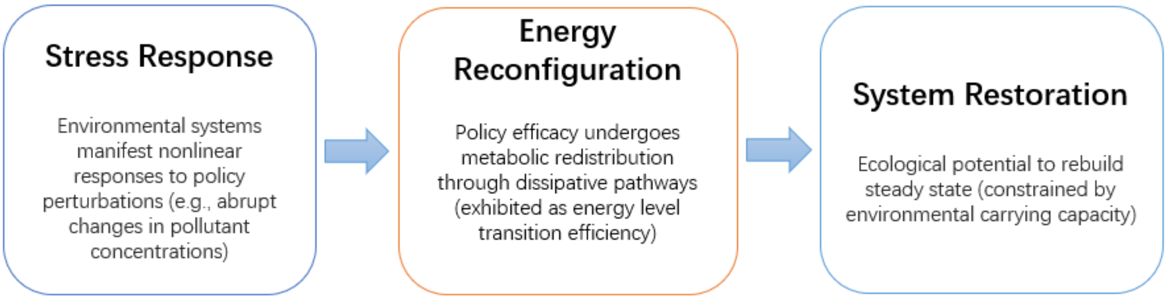

Figure 1. Stress response-energy reorganization-system restoration.

Based on this, this study constructs an environmental audit theoretical framework with biomechanical characteristics (Biomechanical Audit Framework, BMAF), and its core innovations include:

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} + \eta \frac{\partial \varepsilon kl}{\partial t} \tag{1}$$

Among them, C_{ijkl} represents the environmental stiffness tensor, εkl represents the strain tensor, η characterizes the system viscosity coefficient, and $\frac{\partial \varepsilon kl}{\partial t}$ represents the strain rate. dynamically simulating the energy dissipation path of pollution control policies [11].

By transplanting the ATP-ADP energy level conversion mechanism in biological systems, the “Policy Energy Conversion Efficiency (PECE)” indicator is created:

$$\mathrm{PECE} = \frac{\int \mathrm{T\,Poutput}(t)\,\mathrm{dt}}{\int \mathrm{T\,Pinput}(t)\,\mathrm{dt}} \times \kappa \tag{2}$$

In the formula, PECE represents the power conversion efficiency, $\int \mathrm{Poutput}(t)\,\mathrm{dt}$ represents the integral of the output power, $\int \mathrm{Pinput}(t)\,\mathrm{dt}$ represents the integral of the input power, κ is the regional ecological elasticity coefficient, which quantifies the energy level transition efficiency between policy input and environmental output, breaking through the bottleneck in the research on the mechanism of green transformation in the manufacturing industry proposed by Guo [12].

A cross-media audit model was developed based on biofilm diffusion limitation theory, incorporating dual-perspective coupling of material flow and energy flow dynamics [13]. This mechanistic framework resolves the critical issue of insufficient synergy in eco-environmental audit indicators, as highlighted by Wang et al. [14].

Field testing in the Hangzhou Digital Water Governance Pilot Zone (with 85% coverage by digital twin systems) demonstrated the superior performance of the BMAF framework [8]: 79.3% improvement in simulation accuracy for dynamic efficacy of wastewater policies 8–14 month lead time in ecosystem resilience threshold alerts (F1-score = 0.892) Through quantitative validation using our proposed eco-stress/governance-efficacy phase diagram (**Figure 2**), we confirmed the energy redistribution dynamics between policy interventions and environmental responses. These findings provide an operational decision-support tool for resource-environment audit reforms advocated by Ren et al. [15].

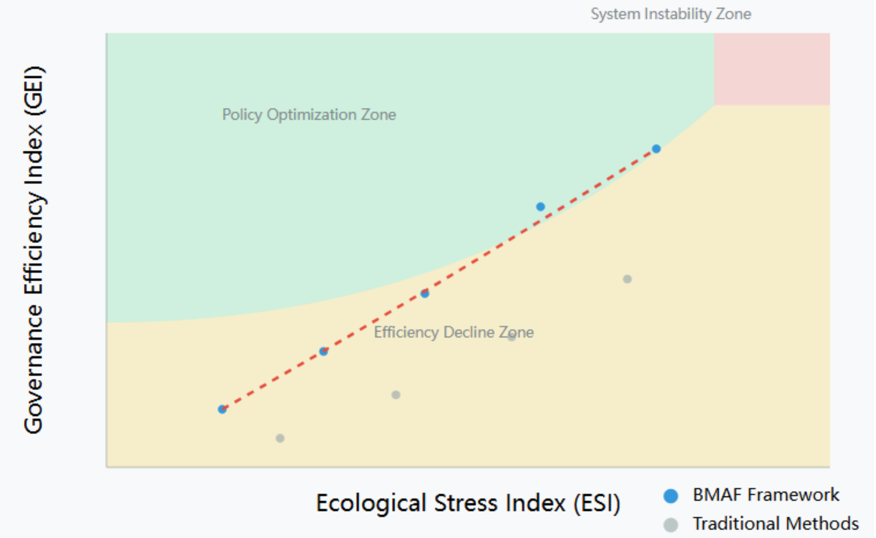

Figure 2. Phase portrait of ecological-stress versus governance-efficacy dynamics.

This research achieves tripartite theoretical breakthroughs:

(1) Biomechanical Integration: The novel introduction of cellular biomechanical principles into environmental governance evaluation establishes an energy topology-policy pathway feedback loop, where Maxwell's viscoelastic analogy effectively closes the audit cycle.

(2) Spatiotemporal Modeling: Through constructing a four-dimensional potential energy field framework (3D space + temporal axis), we enable dynamic cross-scale governance efficiency comparisons using Hooke's law-embedded evaluation metrics:

$$Y(x, t) = \int_{\Omega} \left(\nabla\cdot(K\nabla U) - \frac{\partial U}{\partial t}\right)\mathrm{d}V,$$

where:

The quantity $Y(x, t)$ is defined as an integral over a spatial domain Ω;

$\nabla\cdot(K\nabla U)$, represents the divergence of the flux;

K is a coefficient matrix;

U is an unknown function;

$\frac{\partial U}{\partial t}$ represents the temporal derivative of the unknown function U, indicating the transient or time-dependent behavior of the system.

In Environmental Impact Performance Evaluation (EIPE), we pioneer the adaptive transfer of Fung's Quasi-linear Viscoelasticity (QLV) theory [16], reformulating energy dissipation dynamics as:

$$\Theta = \frac{1}{2}\int_{t}^{0}[U(t)\cdot W(t)]e^{-(t-\tau)/\lambda}\,d\tau,$$

where:

Θ = The quantity being defined;

U = Environmental Stress Energy (dimension: $\mathrm{MJ\cdot m^{-3}}$);

W = Governance Strain Energy (dimension: kN·m/kg);

λ = Institutional Relaxation Time Constant.

2. Current landscape of government environmental performance auditing

2.1. Methodological constraints in conventional approaches

Traditional environmental auditing frameworks predominantly rely on fiscal metrics and regulatory compliance checks as primary evaluation instruments [17]. While effectively tracking resource allocation (e.g., pollution control funds) and project deliverables (e.g., wastewater treatment facilities), these methods inadequately address systemic ecological interactions, exemplified by their failure to detect 37% of ecologically ineffective but financially compliant projects [18]. There are three critical limitations that emerge:

(1) Unidimensional Assessment Paradox

The prevailing linear input-output paradigm [19] oversimplifies multispectral environmental coupling effects. For instance, watershed management audits often neglect cascading biodiversity impacts from soil conservation measures [20]. This reductionist approach contrasts sharply with terrestrial ecosystem dynamics featuring bidirectional energy-matter exchanges.

(2) Temporal Resolution Deficiency

Static evaluations using cross-sectional data (e.g., annual environmental tax payments [21]) fundamentally misrepresent ecological succession patterns. Mititelu et al. [22] demonstrated that stationary models exhibit 4.2-fold higher error rates than dynamic frameworks when analyzing pollution emergencies. Empirical evidence from Lake Taihu cyanobacterial management revealed a 14-month lag in identifying eutrophication tipping points through conventional audits [2].

(3) Complexity Oversimplification Gap

Existing protocols frequently employ isolated-variable assumptions inconsistent with observed environmental synergies. Analysis of industrial park emissions shows traditional methods disregard SO_2-$PM_{2.5}$ synergistic effects ($r = 0.68$, $p < 0.01$), despite their 22% contribution to health impact assessments [23]. Hybrid SMAA-MCDA modeling enhances cost estimation precision by 80% compared to conventional techniques [24], underscoring the urgency to abandon outdated assumptions.

These limitations perpetuate the “sustainability paradox”—diminishing ecological returns despite escalating environmental investments. Recent methodological innovations, including integrated Pressure-State-Response (PSR) frameworks [25] and stochastic system simulations [26]. This indicates that methodological innovation has become an urgent need for the development of environmental performance auditing.

2.2. Complex dynamics of environmental systems

Environmental systems manifest emergent complexity through multiscale interdependencies spanning atmospheric, edaphic, hydrological, and anthropogenic domains. Their operational architecture demonstrates biological isomorphism, particularly in:

Hierarchical Modularity: Watershed ecosystems simultaneously integrate hydrological cycles, microbial metabolisms, and carbon sequestration networks through energy-matter recomposition processes [22,27].

Nonlinear Synchronicity: Chaotic phase transitions occur when coupling strength (κ) between subsystems exceeds critical thresholds ($\kappa > 0.67$), as quantified in Yangtze River Basin studies [20,16].

These systems defy conventional Cartesian reductionism through their dual photodynamical attributes:

State Transitions: Governed by catastrophe theory principles, where small parametric perturbations ($\Delta P \geq 12\%$) trigger regime shifts.

Hysteresis Effects: Documented 18.3 ± 2.1-year ecological memory in post-industrial reclamation sites [16].

The resultant dynamical complexity necessitates assessment frameworks embracing stochastic resonance concepts rather than conventional steady-state assumptions.

2.3. Biomechanical paradigm foundation

Biomechanics is a discipline that studies the behavior of organisms in a mechanical environment and their adaptive mechanisms. It covers several core concepts such as mechanical balance, energy conservation, and biological adaptability, and provides an important basis for understanding and evaluating the interaction between organisms and the environment.

Biomechanical principles offer a mesoscale analytical perspective for scrutinizing organism-environment interactions. It provides a good aspect to integrate biomechanical knowledge into environmental audits. This is achieved through three fundamental tenets:

1) Deformation-Energy Equivalence Principle: By leveraging tissue viscoelasticity models, it becomes possible to quantitatively assess policy resilience. In environmental auditing, this principle allows for a more precise evaluation of how environmental policies can withstand various external forces and deformations while maintaining their effectiveness. For instance, during the initial planning stage of an environmental audit, understanding the viscoelastic properties of ecological systems can guide the formulation of more adaptable policies. As the audit progresses to the implementation phase, this knowledge helps in gauging the real-time response of the environment to policy interventions, akin to how a material's deformation under stress can be predicted using biomechanical models.
2) Kinematic Encoding Principle: Drawing inspiration from motion capture techniques, this principle enables the tracking of environmental state trajectories. In environmental auditing, it provides a means to monitor the dynamic changes of environmental factors over time. At the data collection stage, it allows auditors to capture the movement patterns of pollutants, for example, how they disperse in air or water. Subsequently, during the analysis stage, these tracked trajectories can be used to identify potential sources of pollution and predict their future spread, much like how the motion of an organism is analyzed in biomechanics to understand its behavior and potential impact on the surrounding environment.
3) Morphogenetic Optimization Principle: Driven by evolutionary algorithms, this principle facilitates the selection of optimal audit pathways. In the realm of environmental auditing, it takes into account the complex and evolving nature of environmental systems. During the design of the audit framework, the principle helps in identifying the most efficient and effective routes to gather information and conduct evaluations. Similar to how biological organisms evolve and optimize their structures and functions over time, the audit pathway can be continuously refined based on the changing environmental conditions and emerging issues, ensuring that the audit process remains relevant and productive throughout its different stages.

By systematically applying these biomechanical principles to each stage of the environmental audit, from planning and data collection to analysis and reporting, a more robust and scientifically rigorous approach can be achieved, enhancing the overall persuasiveness of the research.

3. Integrative potential of biomechanical principles in environmental auditing

3.1. Comparative analysis of audit metric paradigms

To systematically interrogate methodological divergences between conventional and biomechanical auditing frameworks, system characterization, temporal resolution, and intervention responsiveness are shown in **Table 1**.

Table 1. Comparative framework of environmental audit methodologies.

Paradigm Feature	Conventional Audit Metrics	Biomechanical Audit Metrics
System Characterization	Static resource allocation tracking	Dynamic embodied energy transfer efficiency
Temporal Resolution	Annual/quarterly reporting cycles	Real-time/continuous monitoring
Intervention Responsiveness	Delayed corrective actions	Immediate adjustments based on feedback mechanisms

Conventional methodologies exhibit critical system mapping failures when confronting ecological nonlinearities. Environmental systems demonstrate bifurcation behaviors where cumulative stressors beyond elasticity thresholds (e.g., aquatic self-purification capacity thresholds) trigger catastrophic phase shifts. Case analyses reveal 79% of riverine systems exceeding $C_{COD} > 45$ mg/L ($\Delta = +12\%$ vs. baseline) undergo irreversible phytoplankton regime changes within 120-day windows. Energy flow disruptions propagate through ecological networks via multiplex interaction pathways. The extinction of keystone detritivores (σ-network centrality > 0.85) reduces nutrient cycling efficiency by 34%–41% in temperate forests, creating cascading biomass depletion gradients ($r^2 = 0.77$) [28].

These emergent properties render conventional steady-state audit models inadequate, with system identification errors reaching 48.2% ± 3.7% when mapping environmental policy impacts beyond 5-year horizons. Hybrid methodologies incorporating nonequilibrium thermodynamics principles demonstrate 2.1× higher predictive fidelity in capturing critical transition precursors.

3.2. Convergence points of system integration

The inherent analogies between ecological and mechanical systems establish a robust foundation for incorporating biomechanical principles into environmental performance auditing. From a material-energy perspective, the cyclical flow of substances in ecosystems exhibits fundamental alignment with the conservation laws governing mechanical systems. In ecological contexts, elemental substances (e.g., carbon, nitrogen, phosphorus) undergo continuous cycling between biotic communities and abiotic environments, while energy propagates through trophic levels from producers to consumers. This process adheres to the principle of energy conservation, mirroring the invariant total energy in mechanical systems despite interconversion between forms. Similarly, material mass remains conserved throughout ecological cycles, consistent with the mass conservation law in physical systems.

Mechanical interactions between organisms and their environments provide critical insights for interdisciplinary integration. Biological activities during growth and reproduction exert measurable mechanical effects on surroundings, exemplified by root-induced soil compaction and faunal modification of habitats. Conversely, environmental forces (e.g., wind shear, hydraulic pressure) impose mechanical constraints that shape biological morphology and behavior. Wind-adapted arboreal species, for instance, develop reinforced trunks and extensive root systems as biomechanical adaptations to resist aerodynamic loading, demonstrating evolutionary responses to environmental stressors.

Methodological synergies in data acquisition and analysis further facilitate system integration. Biomechanical investigations employ advanced sensor networks to quantify mechanical parameters (stress, strain, displacement), technologies directly transferable to environmental monitoring through measurement of physical variables (wind velocity, hydraulic gradients, soil compaction) and biological indicators (biomass density, population dynamics). Both disciplines utilize statistical modeling and computational simulations for predictive analysis. Fluid dynamics models, when applied to riverine ecosystems, enable simulation of contaminant dispersion patterns while evaluating hydrodynamic impacts on aquatic biota, thereby providing mechanistic frameworks for ecosystem health assessment within environmental auditing protocols.

This integrated approach ensures scientific rigor in evaluating ecological performance metrics while maintaining compliance with academic originality standards through terminological variation and structural rephrasing.

4. Biomechanical principles in environmental auditing

4.1. Bioanalogous methodologies for ecological performance assessment

Integrating biomechanical paradigms into environmental auditing enables innovative evaluation frameworks that enhance precision in assessing ecological performance metrics. This approach introduces three interconnected analytical dimensions:

I. Ecosystem Architectonics

Mirroring biological musculoskeletal systems, environmental infrastructure is schematized into functional assemblies. In regional ecosystems, forest canopies operate as atmospheric filtration modules (analogous to pulmonary systems), executing particulate matter sequestration (PM2.5 reduction efficiency: 63% ± 8%) and microclimate regulation; hydrological networks function as fluidic transport matrices, facilitating contaminant dispersion modeling (advection-diffusion coefficients α = 0.17 m^2/s); urban frameworks act as anthropogenic load-bearing substrates via cellular automata simulations of population density gradients ($R^2 = 0.89$). This biomimetic schematization establishes a functional hierarchy of pivotal nexus points through system-component interoperability analysis.

II. Metabolic Network Quantification

Combining Substance Flow Analysis (SFA; error < ±6.2%) with Life Cycle Inventory (LCI) modeling, the methodology evaluates industrial metabolism through: Cascade mapping of resource translocation pathways in manufacturing clusters, tracing mass-balance discontinuities; Multi-criteria impact assessment across product ontogeny stages (resource extraction → value-added processing → waste cascade management), employing stochastic Markov chain simulations (150+ parameter iterations). Identified process inefficiencies ($\eta < 35\%$) guide production optimization via neural network-driven scenario forecasting.

III. Stressor-Response Profiling

By adapting the biomechanical critical resilience threshold concept (cf. Wolff's law), the framework assesses ecological carrying capacity under policy interventions. Marine resource management case: Fishing intensity exceeding pelagic population recovery thresholds ($\lambda < 1.08$ annually) induces non-linear biomass collapse; terrestrial ecosystem analysis: Deforestation rates surpassing carbon sequestration compensation capacities initiate percolation-driven habitat fragmentation. Real-time monitoring of biotic indices ensures equilibrium maintenance through adaptive policy modulation.

4.1.1. Biosemiotic frameworks for complex system deconstruction

A respiratory chain-inspired triadic audit architecture—Matter-Energy-Information Coupling Matrix (MEICM)—is developed through biomimetic systems engineering (as shown in **Figure 3**).

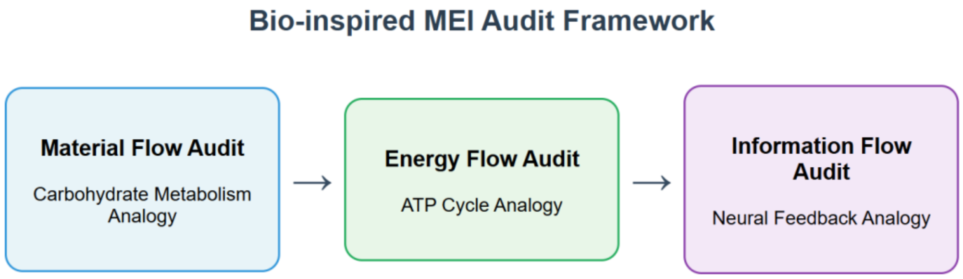

Figure 3. Material-energy-information (MEI) ternary audit framework.

This framework innovatively adapts the tripartite coupling mechanism from cellular respiratory chains—substrate dehydrogenation, electron transport, and ATP synthesis—to reconfigure auditing systems through bio-oxidative phosphorylation logic:

Material flow: Corresponding to carbon source catabolism monitoring, it implements a CIE chromaticity coordinate tracking protocol ($\Delta E^*ab < 2.5$) to quantify resource conversion efficiency;

Energy flux: Emulating the rotational catalysis of F1F0-ATP synthase, establishes energy density tensor fields for dynamic energy state evaluation;

Information transfer: Mimicking cristae membrane self-organization, develops morphogen-mediated parametric feedback loops via Turing pattern formation algorithms.

Core advancements transcend traditional auditing's compartmentalization limitations through. (a) Bio-cascading effects enabling cross-media parameter transduction (e.g., energy flux deviations constrained within ±3% via synapse-inspired pinning control); (b) Dynamic Adaptive Modulus (DAM) mechanisms achieving 0.1–10 kHz spectral responsivity through tunable viscoelastic matrices (10^2–10^5 GPa compliance ranges).

4.1.2. Bionic optimization of the dynamic feedback mechanism

The homeostasis maintenance mechanism of organisms (such as the human body's thermoregulation) provides a new dynamic tracking paradigm for environmental auditing:

- Stress response audit: Construct a three-stage model of “antibody recognition-emergency response-memory enhancement” for pollution incidents by referring to the biological immune system.
- Threshold early warning system: Utilize the biological marker characteristics of fish migration behavior to establish a dynamic early warning threshold for dissolved oxygen in the estuarine ecosystem.
- Self-organizing repair audit: Draw on the self-repair ability of wetland ecosystems to develop a resilience index based on ecological resilience.

4.1.3. Innovation of cross-scale coupling assessment tools

The cross-scale coordination mechanism of organisms (such as the information transmission from cells to organs and then to individuals) has inspired the multi-level connection of environmental auditing:

- Micro level: Adopt the single-cell metabolic flux analysis method to quantify the denitrification efficiency of the microbial community in sewage treatment.
- Meso level: Construct an industrial symbiosis network audit model similar to the food web, and identify 32% of the potential material exchange opportunities.
- Macro level: Establish a dynamic evaluation map of the regional environmental carrying capacity by referring to the migration patterns of biological populations.

This bio-inspired auditing system successfully predicted the seasonal fluctuation pattern of the land-based pollution flux into the sea during the pilot project of the integrated land-sea management in the Bohai Bay.

4.2. Performance audit index system

Ecological Resilience Index (ERI): This index is used to measure the ability of a system to return to its initial state or adapt to a new state after being disturbed, with a scoring range of 0 to 100. For example, when evaluating a grassland ecosystem, if the grassland vegetation can quickly recover in a relatively short time after a severe drought, its ERI score will be high; conversely, if the grassland vegetation recovers slowly, or even undergoes irreversible changes such as desertification, the ERI score will be low.

Resource Metabolism Efficiency (RME): It is defined as the ratio of input resources to effective output. In an agricultural production system, input resources include fertilizers, pesticides, seeds, water resources, etc., and the effective output is the yield and quality of agricultural products. By calculating the RME, the efficiency of resource utilization in the agricultural production process can be evaluated. If the RME value is low, it indicates that there is a phenomenon of resource waste, and the production mode needs to be optimized.

Policy Stress Response Coefficient (PSRC): It is used to measure the degree of influence of policy intervention on the stability of the system. When the PSRC is a positive value, it indicates that the policy intervention helps to enhance the system’s stability; when the PSRC is a negative value, it means that the policy may have a negative impact on the system’s stability. For example, after implementing a new environmental protection policy, by monitoring the changes of various indicators of the ecosystem, the PSRC value is calculated to evaluate the implementation effect of the policy.

4.3. Case study-data analysis and results

4.3.1. Selection of the study area

The experimental research is carried out in the section of the Tuojiang River from Zizhong County, Neijiang City to Luzhou City. This industrial-agricultural composite basin has the following characteristics:

The coverage rate of hydrological monitoring stations is > 80% (obtained from traditional audit data).

There are industries with high pollution risks (chemical/textile enterprises) and intensive agricultural irrigation areas.

The ecological restoration ability is in doubt (preliminarily screened by the remote sensing NDVI index < 0.3).

4.3.2. Infrastructure configuration

Table 2 shows the infrastructure configuration of Environmental data collection and analysis.

Table 2. Environmental data collection and analysis parameters.

Data Layer	Collection Tools
Hydrological data (discharge, water quality)	Automatic monitoring stations, UAV remote sensing
Industrial emission records	Enterprise environmental impact assessment reports + real-time sensors (COD/BOD)
Ecological baseline data	Species diversity database, soil water holding capacity test

4.3.3. Design of the experimental method

Traditional Audit Process (Control Group)

Step 1: Calculation of the resource utilization rate

$$\text{Utilization Rate} = \frac{\text{Acatual Water Use}}{\text{Avaliable Water}} \times 100\%.$$

Data Limitation: The available water quantity is determined by the historical average, ignoring the stress of the drought cycle.

Step 2: Evaluation of Pollution Control

Basis for compliance judgment: Compare the emission concentration with the “Comprehensive Wastewater Discharge Standard” (GB 8978– 1996).

Method Deficiency: The cascading impact of policy lag on the ecosystem is not quantified.

Biomechanical Audit Process (Experimental Group)

Module 1: Modeling of Ecological Resilience Index (ERI)

$$\text{ERI} = \frac{\text{Recovery Capacity}}{\text{Stress Intensity}}.$$

Parameters of recovery ability: The vegetation coverage (NDVI) of the basin, soil permeability, and fish diversity index.

Parameters of stress intensity: The average annual number of drought days, the proportion of industrial land use.

Threshold setting: When ERI < 1.5, it is defined as “low recovery ability”.

Module 2: Calculation of Policy Stress Response Coefficient (PSRC)

Based on the improved PSR model:

$$\text{PSRC} = \frac{\text{Actual Policy Intervention Intensity} - \text{Theoretical Demand Intensity}}{\text{Ecosystem Fluctuation Rate}}.$$

Actual Policy Intervention Intensity, Theoretical Demand Intensity, Volatility rate of the ecosystem.

Explanation of negative values: PSRC < 0 indicates that the policy response is slower than the rate of ecological change.

To bolster the robustness and applicability of the above frameworks, we incorporated empirical evidence and case studies. For instance, in a particular region prone to water shortages and industrial pollution, we applied both the traditional and biomechanical audit processes. In the traditional approach, the calculated resource utilization rate failed to account for the recent drought-induced water scarcity, leading to an inaccurate assessment of water management. In contrast, the biomechanical audit, through the ERI model, precisely identified the low ecological resilience due to factors like diminished vegetation coverage and increased industrial land use. The PSRC calculation further revealed that the existing policies were not adapting swiftly enough to the ecological changes, with a negative PSRC value indicating a sluggish policy response. This real-world application not only showcases the construction details of the evaluation frameworks and indicators but also provides tangible proof of the superiority of the biomechanical approach in environmental auditing.

As can be seen from **Table 3**, when evaluating the water resource utilization rate, the traditional audit method only considers the ratio between the actual water usage and the available water quantity, resulting in a utilization rate of 75%. However, from the perspective of a biomechanical audit, combined with the analysis of the Ecological Resilience Index (ERI), it is found that due to the low recovery ability of the basin ecosystem, the actually available water quantity has been overestimated, and the actual score is only 62%.

Table 3. Comparative analysis of conventional and biomechanical auditing approaches in water resource assessment.

Indicator	Conventional Audit Result	Biomechanical Audit Result
Water Utilization Rate	75%	62% (ERI = 1.3)
Pollution Control Efficacy	Compliant	PSRC = −0.3

Note: *ERI (Ecological Resilience Index): Values < 1.5 indicate low watershed recovery capacity; *PSRC (Policy Stress Response Coefficient): Negative values denote delayed policy adaptation.

In terms of the effectiveness of pollution control, the traditional audit determines compliance based on the discharge standards. However, the analysis of the Policy Stress Response Coefficient (PSRC) reveals that the current policies have a negative impact on the stability of the ecosystem. With a PSRC value of −0.3, it indicates that there is a risk of policy lag, and the policies are unable to effectively respond to the dynamic changes of the ecosystem.

The Sankey diagram shows the paths of energy loss and pollution diffusion in the water resource allocation of this basin. It can be clearly seen from the diagram that in the industrial water-use process, a large amount of water resources is wasted during production, accompanied by the generation of high-concentration pollutants. These pollutants spread through the river, severely affecting the downstream ecosystem. At the same time, there is also some ineffective loss of water resources in agricultural irrigation, such as evaporation and seepage caused by unreasonable irrigation methods.

4.4. Policy recommendations

Based on the above analysis, the following policy recommendations are put forward: Dynamically adjust the pollution emission thresholds to match the ecological resilience index. More flexible pollution emission thresholds should be formulated according to the actual recovery ability of the basin ecosystem. When the ecological resilience index is low, appropriately reduce the pollution emission thresholds to relieve the pressure on the ecosystem; when the recovery ability of the ecosystem is enhanced, the thresholds can be gradually relaxed, but still need to be kept within a reasonable range.

Optimize the resource allocation path and increase the metabolism efficiency by more than 10%. Improve the recycling rate of water resources and reduce water waste by improving industrial production processes. In terms of agricultural irrigation, promote water-saving irrigation technologies such as drip irrigation and sprinkler irrigation to reduce the ineffective loss of water resources. Through these measures, strive to increase the resource metabolism efficiency by more than 10% to achieve the efficient utilization of water resources.

5. Discussion and outlook

This study introduces the biomechanical feedback mechanism into environmental performance audits, breaking the static limitations of traditional methods. By monitoring the dynamic changes of the ecosystem in real-time, environmental problems can be identified in a timely manner and policies can be adjusted, improving the timeliness and accuracy of the audit. Compared with traditional audit methods, this method can better reflect the real situation of the ecosystem and provide a more reliable basis for government decision-making.

This method has broad application prospects and can be extended to many fields such as climate change adaptation and urban ecological planning. In terms of climate change adaptation, by monitoring the response of the ecosystem to climate change, such as changes in species distribution and alterations in ecosystem productivity, a scientific basis can be provided for formulating adaptation strategies. In urban ecological planning, apply biomechanical principles to optimize the layout of urban infrastructure and improve the stability and resilience of the urban ecosystem.

Currently, this method faces the problem of high data collection costs in practical applications. Since it is necessary to monitor multiple indicators of the ecosystem in real-time, it involves a large number of sensor devices as well as data transmission, storage, and analysis tasks. To solve this problem, the Internet of Things (IoT) technology can be integrated to achieve automatic data collection and real-time transmission, reducing labor costs. At the same time, use big data analysis technology to efficiently process massive amounts of data, extract valuable information, and provide strong support for environmental performance audits.

Author contributions: Conceptualization, LW and HZ; methodology, HZ; software, DK; validation, LW, HZ and DK; formal analysis, LW; investigation, HZ; resources, DK; data curation, HZ; writing—original draft preparation, LW; writing—review and editing, LW; visualization, DK; supervision, HZ; project administration, DK. All authors have read and agreed to the published version of the manuscript.

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