SPATIOTEMPORAL ENVIRONMETAL SCREENING AS A BASIS FOR ECOLOGICAL MONITORING OF ENVIRONMENTAL COMPONENTS

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Abstract. Spatiotemporal environmental screening has become an essential component of contemporary environmental monitoring under conditions of increasing anthropogenic pressure, climate change, biodiversity loss, and ecosystem degradation. This review synthesizes current conceptual and methodological approaches to integrated spatiotemporal environmental screening and evaluates the role of biomonitoring, biosurveillance, bioindication, geoinformation technologies, remote sensing, molecular methods, and ecological modeling in comprehensive environmental assessment systems. The study examines the hierarchical organization of environmental screening across multiple levels of ecosystem structure, from molecular and physiological responses to landscape-scale ecological processes. Particular attention is given to the integration of bioindicator systems, environmental DNA (eDNA), metagenomics, GIS technologies, remote sensing platforms, sensor networks, and intelligent analytical approaches for ecosystem diagnostics and ecological forecasting. Methodological aspects of data normalization, multi-criteria assessment, fuzzy logic, spatial interpolation, and the development of integral ecological indices are also analyzed. Based on the reviewed methodological approaches, an integrated spatiotemporal environmental screening framework is proposed. The framework combines data acquisition, ecological screening, analytical integration, ecosystem response assessment, and decision support within an adaptive monitoring cycle. Special emphasis is placed on the development of the Source–State–Risk (SSR) analytical model, which integrates environmental pressures, ecosystem condition, and ecological risks within a unified assessment framework. The reviewed literature suggests that integrating biological indicators, geospatial technologies, remote sensing, molecular approaches, and predictive analytics may strengthen the comprehensiveness and spatial representativeness of environmental monitoring while supporting ecosystem resilience assessment, ecological risk analysis, adaptive environmental management, and evidence-based decision-making.

Key words: spatiotemporal environmental screening; spatiotemporal monitoring; biosurveillance; bioindication; biomonitoring; ecosystem resilience; environmental risk; geospatial analysis; remote sensing; ecological forecasting.

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1. Introduction

Environmental monitoring systems are increasingly challenged by accelerating climate change, intensifying anthropogenic pressures, biodiversity loss, and growing technological risks. These factors substantially complicate environmental assessment, forecasting, and management at local, regional, and global scales. Conventional monitoring approaches often demonstrate limited effectiveness due to fragmented information sources, insufficient integration of biological, chemical, and geospatial data, and inadequate consideration of the spatial and temporal dynamics of ecosystem processes. Consequently, there is a growing demand for integrated environmental assessment frameworks capable of combining heterogeneous ecological information within unified analytical systems (Hasan, 2024).

The rapid development of digital technologies, satellite monitoring systems, artificial intelligence, and multi-source environmental data integration platforms is shaping a new paradigm of ecological monitoring focused not only on the accumulation of primary information, but also on its analytical interpretation, predictive modeling, and ecological risk forecasting. Recent review studies demonstrate that the integration of GIS, RS, multi-sensor technologies, and machine learning approaches significantly improves the accuracy of ecosystem state assessment, facilitates the identification of hidden ecological patterns, and enhances the capacity for real-time spatiotemporal analysis of environmental processes (Álvarez-Martínez et al., 2026; Hwang et al., 2025, Nahurskyi et al., 2024). Furthermore, integrated monitoring approaches contribute to ecological risk assessment, ecosystem resilience evaluation, and adaptive environmental management under conditions of increasing environmental uncertainty (Javan et al., 2025; Jodhani et al., 2026).

Despite these advances, the development of comprehensive analytical frameworks capable of integrating biological, ecological, spatial, and temporal datasets within unified environmental assessment systems remains a major scientific challenge. Existing approaches are frequently limited to individual indicators or specific ecosystem components, which constrains their applicability for comprehensive ecosystem assessment, ecological risk analysis, and predictive environmental modeling.

Therefore, the objective of this study is to synthesize contemporary methodological approaches to spatiotemporal environmental screening and to propose an integrated conceptual framework for environmental monitoring that brings together biomonitoring, biosurveillance, biotesting, geographic information systems (GIS), remote sensing, and multi-source environmental data. The proposed framework is intended to provide a conceptual basis for linking heterogeneous environmental observations across spatial and temporal scales and for supporting ecosystem diagnostics, ecological risk analysis, and adaptive environmental decision-making.

2. Review Methodology

2.1. Literature Search and Selection Procedure. The present study was conducted as an integrative narrative review aimed at synthesizing contemporary methodological approaches to spatiotemporal environmental screening, biomonitoring, biosurveillance, ecological risk assessment, and geospatial ecosystem analysis. The review focused on identifying major conceptual developments, methodological approaches, technological tools, and analytical frameworks relevant to the integration of heterogeneous environmental data within spatiotemporal monitoring systems. Based on this synthesis, an integrated conceptual framework for environmental monitoring was proposed, bringing together biomonitoring, biosurveillance, biotesting, geographic information systems (GIS), remote sensing, and multi-source environmental data.

The literature search was conducted using four scientific information sources: Scopus, Web of Science, ScienceDirect, and Google Scholar. The primary literature search covered publications published between 2000 and 2025, with particular emphasis on studies published during the last decade because of the rapid development of remote sensing, geographic information systems (GIS), environmental DNA (eDNA), sensor technologies, artificial intelligence, and integrated environmental monitoring platforms. Earlier publications were retained when they provided fundamental theoretical or methodological contributions to biomonitoring, ecosystem assessment, ecological resilience, environmental indicators, or ecological risk analysis. An additional literature search update was conducted in 2026 to identify recently published studies directly relevant to the reviewed topic and to ensure that the synthesis reflected current methodological developments.

The search strategy combined terms describing the methodological concept, environmental monitoring approaches, analytical technologies, and ecological assessment objectives. The principal search terms and thematic clusters included: “spatiotemporal environmental screening”, “biomonitoring”, “biosurveillance”, “bioindication”, “ecological risk assessment”, “GIS-based environmental monitoring”, “remote sensing”, “ecosystem resilience”, “environmental DNA”, “integrated ecosystem assessment”, “ecological indicators”, “multi-criteria environmental analysis”, “fuzzy logic”, and “predictive ecological modeling”. The terms were combined using Boolean operators, primarily AND and OR, and adapted to the syntax of the respective information sources.

The identification and selection of relevant publications followed a sequential qualitative screening procedure. Records retrieved from the different information sources were examined for their relevance to the thematic scope and objectives of the review. Duplicate records and publications clearly outside the research objectives were excluded from further consideration. Titles and abstracts were subsequently screened to identify potentially relevant studies, followed, where appropriate, by examination of the full text. Particular attention was given to the methodological relevance of each publication and to its contribution to the understanding or application of integrated environmental monitoring approaches.

The inclusion criteria comprised peer-reviewed research articles, review papers, methodological studies, and conceptual or analytical frameworks addressing integrated environmental assessment, ecosystem diagnostics, spatiotemporal ecological analysis, environmental forecasting, ecological indicators, GIS-supported monitoring, remote sensing, biomonitoring, biosurveillance, bioindication, or ecological risk assessment. Priority was given to studies demonstrating integration of biological, geospatial, molecular, physicochemical, or analytical approaches, as well as studies addressing hierarchical monitoring systems and risk-oriented ecosystem assessment. Publications were excluded when they were unrelated to environmental monitoring or ecological assessment, addressed isolated technical or biological processes without relevance to integrated environmental analysis, or did not provide sufficient methodological or conceptual information for the objectives of the review.

The selected literature was subjected to qualitative comparative and thematic analysis. The synthesis focused on methodological trends, analytical limitations, emerging technological directions, and opportunities for developing integrated spatiotemporal environmental screening systems. The reviewed studies were organized according to the principal methodological components of integrated environmental monitoring, including biological indicators, biosurveillance, GIS and remote sensing, molecular approaches, multi-criteria analysis, ecological indices, predictive modeling, and decision-support frameworks.

Because the study was designed as an integrative narrative review rather than a systematic review or meta-analysis, the objective was not to calculate pooled effect sizes or perform statistical meta-analysis. Instead, the literature was synthesized thematically to identify converging methodological approaches, complementary analytical tools, current limitations, and potential directions for the development of integrated spatiotemporal environmental screening frameworks. The final qualitative synthesis comprised 28 publications selected as directly relevant to the conceptual and methodological objectives of the study, including publications identified during the 2026 search update.

2.2. Conceptual Framework of Integrated Spatiotemporal Environmental Screening. In this study, an integrated spatiotemporal environmental screening framework is proposed that combines biomonitoring, biosurveillance, biotesting, geographic information systems (GIS), remote sensing technologies, and multi-source environmental data within a unified information-analytical architecture.

Unlike conventional environmental monitoring approaches, which frequently rely on isolated indicators or individual ecosystem components, the proposed framework is designed to transform heterogeneous environmental observations into an integrated system of ecological indicators characterizing ecosystem state, resilience, functional stability, ecological risk, and adaptive capacity. The framework integrates ecological screening, analytical assessment, ecosystem resilience evaluation, and environmental decision-support components within a comprehensive monitoring structure (Fig. 1).

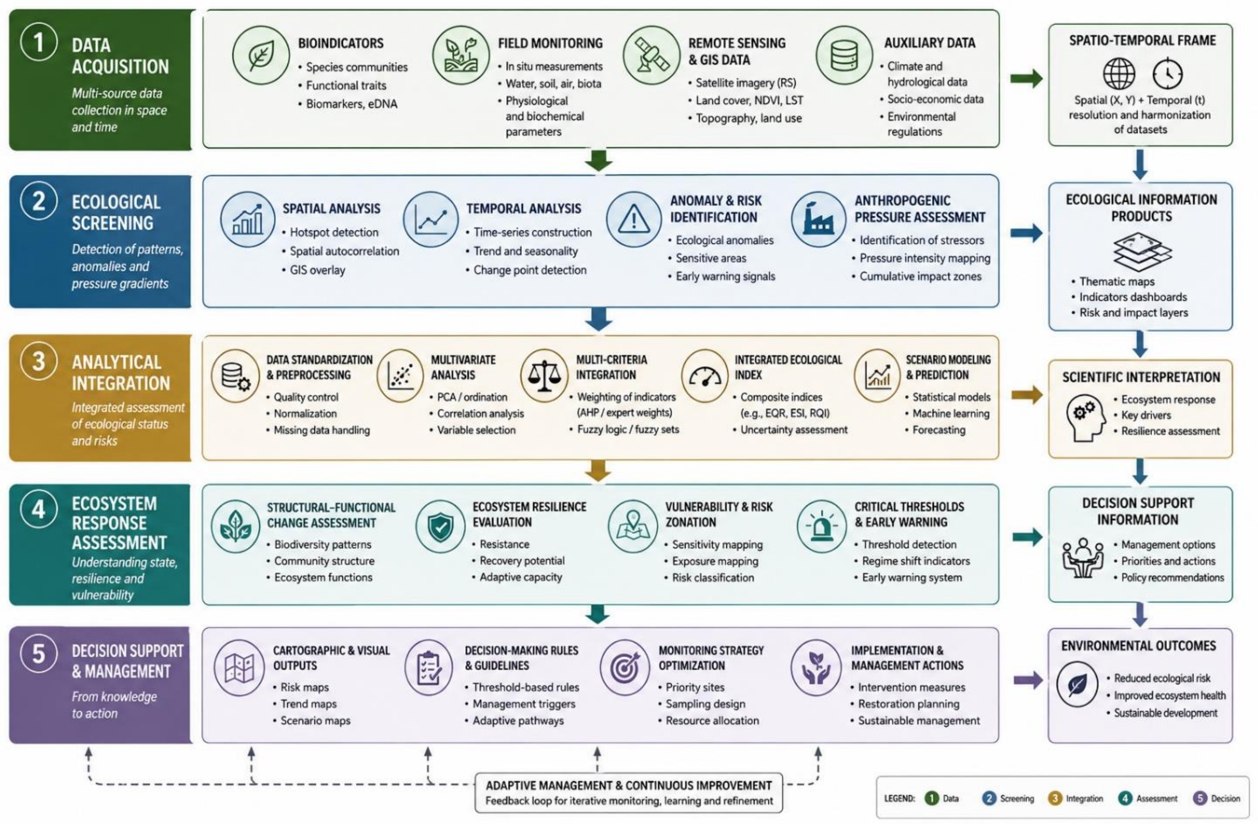

Fig. 1. Hierarchical conceptual framework of integrated spatiotemporal environmental screening

Figure 1 illustrates the hierarchical conceptual framework of integrated spatiotemporal environmental screening proposed in this study. The framework integrates biomonitoring, biosurveillance, biotesting, remote sensing, geographic information systems (GIS), and multi-source environmental data within a unified analytical architecture. It comprises five interconnected analytical levels: (1) data acquisition, integrating biological, environmental, geospatial, and auxiliary datasets; (2) ecological screening, focused on identifying environmental patterns, anomalies, and anthropogenic pressures; (3) analytical integration, including data standardization, multi-criteria analysis, ecological index development, and predictive modeling; (4) ecosystem response assessment, encompassing resilience, vulnerability, and ecological risk analysis; and (5) decision support and environmental management, providing evidence-based recommendations for adaptive environmental governance. The framework also incorporates a spatiotemporal analytical dimension and an adaptive management feedback loop, supporting ecosystem diagnostics, resilience assessment, ecological forecasting, and evidence-based decision-making under conditions of environmental uncertainty.

These components are functionally interconnected. Data acquisition provides the empirical basis for ecological screening; screening identifies relevant spatial and temporal patterns and environmental pressures; analytical integration transforms heterogeneous observations into standardized indicators and risk-related information; ecosystem response assessment interprets these outputs in terms of resilience, vulnerability, and ecological risk; and decision support translates the analytical results into management recommendations. Feedback from management informs subsequent monitoring and data acquisition, thereby establishing an adaptive cycle of observation, analysis, interpretation, and management response.

The conceptual novelty of the proposed framework lies in the integration of multi-level ecological indicators, geospatial analytical methods, ecosystem productivity assessment, and risk-oriented environmental modeling within a unified spatiotemporal analytical architecture. Furthermore, the framework incorporates the conceptual principles of the Source–State–Risk (SSR) model as a methodological basis for ecological risk differentiation, ecosystem resilience assessment, and evidence-based environmental decision support.

The methodological foundation of the proposed framework combines GIS technologies, remote sensing, fuzzy logic methods, data normalization procedures, weighted ranking approaches, ecological index analysis, and artificial intelligence tools. This integration may improve the reliability and consistency of environmental assessment, facilitates the identification of spatiotemporal patterns of ecosystem transformation, supports the detection of early ecosystem degradation processes, and strengthens predictive ecological analysis. Despite substantial advances in integrated environmental monitoring systems, the analytical integration of biological, geospatial, and multi-source environmental datasets within unified spatiotemporal assessment frameworks remains insufficiently developed, highlighting the scientific relevance and practical significance of the proposed approach (Javan et al., 2025; Jodhani et al., 2026).

3. Conceptual Foundations of Spatiotemporal Environmental Screening

Spatiotemporal environmental screening is conceptualized in this study as an integrated analytical approach for detecting, spatially localizing, interpreting, and forecasting ecosystem transformations on the basis of heterogeneous ecological indicators. Its conceptual foundation combines biomonitoring, biosurveillance, bioindication, geoinformation technologies, remote sensing, molecular-biological methods, and analytical modeling within a common spatiotemporal framework. Unlike conventional monitoring systems that are frequently organized around individual environmental components or isolated measurement procedures, spatiotemporal screening emphasizes the coordinated interpretation of biological responses, environmental drivers, spatial patterns, and temporal dynamics.

The methodological rationale for such an approach derives from the increasing complexity of environmental change and the need to distinguish natural ecosystem variability from anthropogenically induced transformations. Contemporary monitoring systems increasingly incorporate GIS platforms, remote sensing, sensor networks, ecological indicators, and intelligent analytical tools to characterize environmental changes across multiple spatial and temporal scales. The integration of these approaches may improve the spatial representativeness, comparability, and analytical reliability of ecological observations, particularly under conditions of increasing anthropogenic pressure and climate change (Lindenmayer & Likens, 2010; Ullo & Sinha, 2020; Soubry et al., 2021).

A fundamental characteristic of spatiotemporal environmental screening is its multi-level organization. Ecological responses may be considered across a hierarchy extending from molecular and subcellular alterations through physiological and organismal responses to population, community, ecosystem, and landscape-level transformations. Such hierarchical organization provides a basis for linking early biological responses with subsequent structural and functional changes at higher levels of ecological organization. Molecular and genetic approaches, including environmental DNA (eDNA), metabarcoding, metagenomics, bioinformatics, and high-throughput sequencing, have considerably expanded the capacity to detect changes in biodiversity and community composition. These methods are particularly relevant where conventional observations may not reveal early or cryptic ecosystem disturbances (Ruppert et al., 2019; Dugal et al., 2022, 2023; Yoon et al., 2025; van der Heyde et al., 2022).

Within this conceptual architecture, three complementary functional components can be distinguished: screening, biosurveillance, and biomonitoring. Screening is primarily concerned with the rapid detection of ecological anomalies, identification of potentially affected areas, and spatial localization of environmental risk zones. Biosurveillance represents the continuous observation of ecological systems over extended periods, with particular attention to stochastic fluctuations, successional trajectories, and adaptive responses of biological communities. Biomonitoring provides standardized quantitative characterization of ecosystem responses using biological and environmental indicators and supports the verification of patterns identified during screening and biosurveillance. Bioindication constitutes an important analytical mechanism within this system by translating biological responses into information about environmental conditions and stressors. Thus, screening, biosurveillance, and biomonitoring represent complementary rather than interchangeable functions within an integrated spatiotemporal framework.

The ecological interpretation of screening results requires consideration of three interconnected groups of determinants: biological characteristics, endogenous ecosystem processes, and exogenous environmental drivers. Biological characteristics include species-specific tolerance, adaptive potential, ecological plasticity, and niche breadth. Endogenous processes encompass succession, population dynamics, physiological regulation, biochemical interactions, and other processes generated within ecosystems. Exogenous drivers include climatic variability, seasonal dynamics, habitat transformation, pollution, and other anthropogenic pressures. Their interaction determines the magnitude, spatial distribution, and temporal trajectory of ecosystem responses and provides the analytical basis for identifying deviations from expected ecological conditions.

Biological responses are particularly valuable because they integrate the effects of multiple environmental stressors that may not be adequately represented by measurements of individual pollutants or physicochemical parameters. Experimental biomonitoring studies using model organisms have demonstrated that physiological and behavioral alterations can provide sensitive evidence of environmentally induced stress. For example, studies of Drosophila melanogaster have reported physiological and behavioral changes associated with exposure to anthropogenic contaminants such as bisphenol A, supporting the use of biological responses in early ecological diagnostics (Gaivão et al., 2025). Cytogenetic biomarkers provide another level of biological information, with micronucleus-based approaches demonstrating sensitivity to environmentally induced genomic instability and long-term anthropogenic effects on biological systems (Rudenko et al., 2002)

Consequently, indicator selection represents a central methodological task in spatiotemporal environmental screening. Indicators should be sufficiently sensitive to environmental stressors, diagnostically informative, reproducible, and representative of the ecological level under investigation. Their interpretation should also account for spatial heterogeneity, temporal variability, and the possibility of interacting or cumulative stressors. A multi-indicator strategy is therefore preferable to reliance on isolated variables, particularly where ecosystem responses emerge through interactions among biological, physicochemical, and climatic factors.

The integration of heterogeneous indicators requires analytical procedures capable of preserving both their individual information content and their relationships within the ecosystem. Multi-criteria analysis, GIS-based overlay procedures, principal component analysis (PCA), fuzzy logic, and integral index approaches can be used to identify multidimensional patterns and synthesize complementary indicators into interpretable ecological metrics (Li et al., 2020; Markert et al., 2003). Such procedures are particularly relevant for spatiotemporal screening because ecological degradation rarely manifests as a change in a single variable; rather, it emerges as a coordinated shift in several biological, environmental, and spatial characteristics.

A further methodological dimension is provided by the integration of geospatial and remote-sensing technologies. GIS platforms, satellite observations, sensor networks, and unmanned aerial systems extend ecological observations beyond individual sampling locations and provide spatially explicit information on habitat structure, vegetation dynamics, fragmentation, land-cover transformation, and environmental process patterns. Remote sensing can provide repeated observations over large territories, whereas GIS facilitates the integration of spatial layers with field-based biological and physicochemical measurements. Their combined application strengthens the spatial component of environmental screening and provides a basis for identifying areas requiring more detailed field investigation (Soubry et al., 2021; Estoque & Murayama, 2017; Shomko & Davydova, 2024).

Molecular-biological and chemical-analytical methods complement this spatial framework by providing information at finer biological and physicochemical levels. eDNA analysis, metabarcoding, biomarkers, and high-throughput sequencing can reveal changes in biodiversity, community composition, and biological integrity that may precede visually detectable ecosystem degradation (Ruppert et al., 2019; Dugal et al., 2022). At the same time, highly sensitive electrochemical, chromatographic, and spectrophotometric methods contribute to the detection and characterization of emerging contaminants. Recent studies of sucralose determination and electroanalytical detection of herbicide residues illustrate the expanding role of advanced analytical techniques in environmental screening (Tkach et al., 2025a; Tkach et al., 2025b; Milyukin & Gorban, 2023). These methods should therefore be regarded as complementary analytical layers rather than independent monitoring systems.

The temporal dimension is equally important. Permanent or repeatedly surveyed monitoring sites provide the empirical basis for distinguishing short-term fluctuations from persistent trends and directional ecosystem transformations. When such observations are spatially organized within GIS environments, indicator trajectories can be compared among ecotopes characterized by different environmental conditions or levels of anthropogenic pressure. This spatially structured observation network creates a basis for detecting anomalies, identifying persistent changes, analyzing ecological trajectories, and developing scenario-based forecasts.

The theoretical interpretation of these trajectories is closely associated with ecological resilience, adaptive capacity, vulnerability, and regime-shift concepts. Ecosystems may undergo substantial functional reorganization when environmental pressures exceed critical thresholds, potentially resulting in transitions toward alternative ecological states. Spatiotemporal screening therefore extends beyond the registration of environmental change and focuses on the identification of patterns that may indicate declining resilience, increasing vulnerability, or approaching functional thresholds. This orientation strengthens the prognostic component of monitoring and provides a conceptual basis for linking empirical observations with environmental management and decision-support processes.

From an operational perspective, integrated spatiotemporal environmental screening can be represented as a sequence of interconnected analytical stages: selection of representative observation sites; standardized acquisition of biological, physicochemical, molecular, and spatial data; preprocessing and harmonization of heterogeneous observations; indicator characterization; spatial and temporal analysis; identification of ecological anomalies and risk zones; and scenario-based interpretation and forecasting. The stages are not strictly linear, because the results of spatial analysis, validation, or forecasting may require additional observations or refinement of the indicator system. This recursive structure distinguishes an adaptive screening framework from conventional monitoring schemes based on isolated measurement cycles.

The rapid development of environmental monitoring technologies has resulted in a broad range of approaches differing in biological sensitivity, spatial coverage, temporal resolution, analytical complexity, and predictive potential (Table 1). Biomonitoring provides detailed information on biological responses but may have limited spatial extrapolation. Remote sensing offers extensive spatial coverage but generally provides less direct biological specificity. eDNA and related molecular approaches provide high taxonomic sensitivity but require methodological standardization and appropriate reference databases. GIS-integrated screening provides a mechanism for combining heterogeneous spatial and ecological information, although its effectiveness depends on data quality, compatibility, and analytical infrastructure.

Table 1

Comparative Analysis of Major Approaches Used in Spatiotemporal Environmental Screening

Approach	Strengths	Limitations	Spatial Scale	Predictive Capacity
Biomonitoring	High biological sensitivity; direct characterization of organismal and community responses	Limited spatial extrapolation; dependence on field sampling	Local–regional	Moderate
Remote sensing	Large-scale and repeated spatial coverage; high temporal frequency for selected variables	Lower biological specificity; indirect representation of many ecological processes	Regional–global	High
eDNA	High taxonomic sensitivity; detection of cryptic or low-abundance taxa	Standardization, reference-database, and contamination-control challenges	Local–regional	Moderate
GIS-integrated screening	Multi-layer integration; spatial visualization; compatibility with heterogeneous datasets	High data and methodological complexity; dependence on data quality	Multi-scale	High

The comparison indicates that no individual approach adequately represents the multidimensional nature of ecosystem transformation. The principal methodological limitations of existing systems include fragmentation among monitoring components, incompatibility of spatial and temporal scales, heterogeneous data structures, restricted transferability of local observations, and insufficient integration of biological responses with environmental drivers. Approaches optimized for broad spatial coverage may lack biological specificity, whereas highly sensitive biological or molecular techniques may provide limited spatial extrapolation. Consequently, the principal methodological challenge is not the absence of individual monitoring technologies but the insufficient integration of their complementary information within a common analytical architecture.

This methodological gap provides a rationale for integrated spatiotemporal environmental screening frameworks that combine bioindication, biomonitoring, biosurveillance, geospatial technologies, remote sensing, molecular-biological methods, ecological indices, and predictive modeling. Such integration creates a hierarchical analytical system in which observations obtained at different biological and spatial levels can be interpreted jointly rather than treated as independent datasets. The resulting framework is intended to support the detection of ecological anomalies, differentiation of natural and anthropogenic transformations, identification of cumulative stressor effects, characterization of ecosystem trajectories, and development of evidence-based environmental management responses.

From a conceptual perspective, spatiotemporal environmental screening can therefore be represented as a hierarchical and recursive process in which environmental drivers generate ecosystem responses, observations characterize the resulting state, and analytical procedures transform heterogeneous observations into spatially and temporally explicit information about ecological change and potential risk. This interpretation establishes a direct connection between empirical monitoring and predictive ecological analysis and provides the conceptual foundation for the subsequent formalization of the screening methodology.

The relationships among environmental pressures, ecosystem responses, and potential consequences can be summarized using a Source–State–Risk (SSR) perspective. In this framework, Source represents environmental pressures and drivers, including anthropogenic, climatic, and other external influences; State represents the structural, functional, biological, and physicochemical characteristics of the ecosystem resulting from the interaction of these drivers with endogenous processes; and Risk represents the potential ecological consequences associated with observed or projected changes in ecosystem state. Monitoring and screening data provide the empirical basis for establishing relationships among these three components across spatial and temporal scales. The SSR perspective consequently provides a conceptual bridge between heterogeneous environmental observations, ecosystem diagnostics, ecological forecasting, and subsequent formalization of an integrated spatiotemporal monitoring framework.

4. Operational Architecture of Integrated Spatiotemporal Environmental Screening

The implementation of integrated spatiotemporal environmental screening frameworks generally involves several interconnected procedural stages, each performing a specific diagnostic and analytical function within the overall ecosystem assessment system. Contemporary environmental monitoring studies increasingly emphasize the importance of combining spatial representativeness, multi-level bioindication, geospatial analysis, productivity assessment, and integral ecological indices within unified analytical architectures capable of supporting adaptive environmental management and ecological forecasting (Lindenmayer & Likens, 2010; Soubry et al., 2021).

Selection of Representative Ecotopes. The first stage involves the identification of representative ecotopes based on geographical, climatic, landscape, and ecological criteria, taking into account regional heterogeneity and gradients of anthropogenic pressure. Such an approach creates the basis for the spatial extrapolation of monitoring results, comparative analysis of ecosystem responses, and differentiation of environmental transformations under varying natural and anthropogenic conditions. The establishment of spatially distributed monitoring networks considerably improves the representativeness and reliability of environmental assessment systems, particularly within heterogeneous landscapes and ecologically fragmented territories (Lindenmayer & Likens, 2010).

Bioindication and Early Ecological Diagnostics. The bioindication stage is focused on the application of sensitive biological indicators capable of responding to a broad spectrum of environmental stressors. Contemporary screening systems increasingly integrate morphometric, physiological-biochemical, cytogenetic, and behavioral indicators in order to improve the sensitivity of ecological diagnostics and to identify ecosystem destabilization at early stages.

Particular importance is attributed to the analysis of fluctuating asymmetry, stress-induced morphophysiological alterations, mutation frequency, and adaptive responses of model organisms, which provide quantitative information regarding the intensity of biotic stress and ecological disturbance. Such approaches considerably expand the analytical capabilities of conventional environmental monitoring systems by reflecting not only pollutant concentrations, but also the integrated biological consequences of anthropogenic impacts (Markert et al., 2003; Gaivão et al., 2025).

Geobotanical Analysis and Phytoindication. Geobotanical assessment and phytoindication constitute essential components of integrated spatiotemporal screening frameworks. These approaches involve the analysis of floristic composition, species diversity, phytocoenotic structure, and ecological differentiation of plant communities using standardized ecological and phytosociological methods, including the Braun-Blanquet approach, biodiversity indices, and ecological indicator scales.

The application of phytoindication scales reflecting light availability, moisture conditions, trophic status, salinity tolerance, and other environmental gradients contributes to the identification of ecological shifts and long-term habitat transformations. In addition, species tolerance indices may serve as quantitative indicators of adaptive potential, ecosystem stability, and resistance of biological communities to environmental stressors. Similar approaches are increasingly employed in ecosystem health assessment systems integrating vegetation indicators, GIS analysis, and spatial ecological diagnostics (Soubry et al., 2021; Boori et al., 2021; Gerasymenko et al. 2025).

Assessment of Ecosystem Productivity and Functional Stability. An important analytical component of spatiotemporal environmental screening involves the assessment of ecosystem productivity and functional organization. Contemporary ecosystem monitoring frameworks increasingly employ indicators such as gross primary productivity (GPP), net primary productivity (NPP), biomass accumulation, and growth dynamics of woody and herbaceous species for evaluating ecosystem functioning and ecological efficiency.

These parameters reflect the energetic organization of ecosystems and provide valuable information regarding ecosystem resilience, adaptive capacity, and sensitivity to environmental disturbances. The integration of productivity indicators with bioindication and geospatial analysis substantially enhances the prognostic potential of ecosystem assessment systems and improves the identification of degradation processes under conditions of climatic variability and anthropogenic pressure (Rocha et al., 2021).

In agroecosystem contexts, productivity assessment is closely linked to pollination services and landscape-level ecological interactions. Recent field-based studies have demonstrated that the integration of nectar-producing plants into crop rotation systems significantly enhances pollinator activity, improves floral resource continuity, and increases crop yield through improved ecosystem functioning and pollination efficiency (Mudrak et al., 2025). Such findings highlight the importance of incorporating biotic interaction networks into spatiotemporal environmental screening frameworks, particularly when assessing ecosystem services and agroecological stability.

Data Normalization and Integral Ecological Indices. The integration of heterogeneous ecological parameters represents one of the central methodological challenges of spatiotemporal environmental screening. To improve analytical consistency and comparability, contemporary environmental assessment systems increasingly employ normalization procedures, weighted coefficients, multi-criteria analysis, fuzzy logic approaches, and integral ecological indices.

Integral indicators such as Ecosystem Stress Index (ESI), Ecological Hazard Index (EHI), and Zonation Disturbance Index (ZDI) may be applied for the quantitative characterization of ecosystem condition and ecological risk differentiation. The use of weighted analytical models enables the consideration of the relative contribution and diagnostic significance of individual indicators within the integrated assessment framework. Similar methodological principles have been reported in GIS-supported ecosystem health assessment and integrated ecological evaluation studies (Soubry et al., 2021; Zhang et al., 2023).

Hierarchical Structural Model of Spatiotemporal Environmental Screening. Integrated spatiotemporal environmental screening may be represented as a hierarchical methodological system in which each analytical level functions as a logical continuation of the previous one while simultaneously creating the basis for higher-order ecological generalization and predictive assessment. Such hierarchical architectures improve the integrity of ecosystem analysis and strengthen the applicability of environmental monitoring systems for ecological forecasting and adaptive environmental governance (Lindenmayer & Likens, 2010).

At the conceptual level, spatiotemporal environmental screening is interpreted as an integrated ecological "check-up" system aimed at detecting transformations within biotic, abiotic, and biogeochemical ecosystem components. This level is based on contemporary concepts of ecosystem dynamics, ecological resilience, biomonitoring, biosurveillance, and risk-oriented environmental assessment.

At the methodological level, the conceptual framework is implemented through a modular analytical architecture integrating bioassays, bioindication, stoichiometric analysis, photometric and spectral-index approaches, microcosm experiments, GIS-based spatial analysis, and environmental modeling tools. The integration of these modules creates a multidimensional analytical platform capable of processing heterogeneous ecological information originating from different levels of ecosystem organization. Contemporary ecosystem monitoring systems increasingly combine remote sensing, GIS technologies, ecological indicators, and integrated analytical models within unified environmental assessment platforms (Soubry et al., 2021).

The operational integration of biological indicators, geospatial technologies, productivity analysis, ecological indices, and predictive modeling contributes to the development of adaptive ecosystem screening systems oriented toward early ecological diagnostics, spatial differentiation of environmental risks, and evidence-based environmental decision support under conditions of increasing ecological uncertainty and global environmental change. Recent environmental monitoring studies also emphasize the growing role of integrated geospatial frameworks and ecosystem resilience assessment for large-scale environmental diagnostics and sustainable ecosystem management (Lindenmayer & Likens, 2010; Rocha et al., 2021).

5. Hierarchical and Source–State–Risk (SSR) Analytical Framework

At the integrative level, spatiotemporal environmental screening involves the fusion of heterogeneous datasets, including field measurements, laboratory analyses, remote sensing products, and experimental observations, within a unified spatiotemporal analytical framework. This level functions as a methodological backbone that harmonizes differences in spatial resolution, temporal scales, and data structure, thereby ensuring analytical consistency across multi-source environmental information systems.

The index-based analytical level focuses on the transformation of integrated datasets into generalized ecological indicators. This stage incorporates data normalization, weighting procedures, fuzzy logic approaches, spatial interpolation, and statistical smoothing techniques. As a result, a set of composite ecological indices is derived, enabling comparability among heterogeneous environmental parameters and supporting integrated ecosystem assessment within a unified analytical framework.

At the predictive and risk-oriented level, integrated indices are combined with biosurveillance data, microcosm experimental results, and satellite-derived environmental indicators to support spatial modeling and ecological forecasting. This approach enables the identification of high-risk ecological zones, detection of critical degradation hotspots, and analysis of spatiotemporal trends in ecosystem transformation.

The Source–State–Risk (SSR) model represents a core conceptual component of the proposed framework and provides a causal analytical structure linking environmental pressures, ecosystem condition, and ecological risk. Similar cause–effect structures are widely applied in integrated environmental assessment systems and risk-oriented ecological modeling frameworks.

The SSR model consists of three interrelated components:

Source, represented by a Pollution Load Index (PLI), integrating contaminant concentrations, physicochemical environmental properties, and toxicological potential;

State, represented by an Ecosystem Condition Index (ECI), reflecting biodiversity structure, ecological integrity, and functional stability;

Risk, quantified through genetic hazard indicators, including mutation frequency, chromosomal aberrations, and micronuclei formation, as well as a Mutagenic Risk Index (MRI), reflecting the probability of population-level genetic destabilization.

The synthesis of these parameters results in an Ecological Safety Index (EcoSI), which enables integrated assessment of ecosystem status, spatial identification of environmental risk zones, and prediction of potential system destabilization. Application-based studies reported in the literature demonstrate the effectiveness of such integrated frameworks in identifying spatial patterns of chemical accumulation and ecosystem response under anthropogenic pressure (Grytsenko et al., 2024).

Further development of the SSR framework increasingly relies on fuzzy logic methods and multi-criteria decision analysis, enabling improved handling of ecological uncertainty and multidimensional environmental datasets. This supports the derivation of advanced composite indicators, including Urban–Natural Balance Index (UNBI), Chemical Deviation Index (CDI), Mutagenic Risk Index (MRI), and Ecological Safety Index (EcoSI), which collectively form the analytical core of spatiotemporal environmental screening systems.

4. Conclusions

The reviewed literature suggests that spatiotemporal environmental screening can serve as a useful conceptual basis for integrating heterogeneous information on environmental pressures, ecosystem condition, and ecological responses. The synthesis indicates that biological indicators, biomonitoring, biosurveillance, biotesting, GIS, remote sensing, molecular approaches, and multi-source environmental data can be considered complementary components of integrated environmental monitoring.

The proposed framework organizes these components into a hierarchical analytical architecture comprising data acquisition, ecological screening, analytical integration, ecosystem response assessment, and decision support. The operational sequence further links monitoring-site selection, indicator selection, data acquisition, preprocessing, normalization, index construction, spatial analysis, risk classification, interpretation, and adaptive feedback.

The proposed Source–State–Risk (SSR) model provides a conceptual structure for linking environmental pressures with ecosystem condition and potential ecological risk. Its integration with spatiotemporal analysis may support the interpretation of heterogeneous environmental information and the development of adaptive monitoring and decision-support approaches.

Because the framework was developed through an integrative narrative synthesis, its applicability and analytical performance require further empirical testing using independent environmental datasets and case-specific monitoring programmes. Future research should therefore focus on operational implementation, parameterization, validation, uncertainty analysis, and comparison of the proposed framework with established environmental monitoring and risk-assessment approaches.

Further development of integrated spatiotemporal environmental screening should focus on the incorporation of artificial intelligence, automated sensor networks, environmental DNA technologies, digital ecosystem twins, and adaptive forecasting models to support real-time environmental assessment and decision-making under conditions of global environmental change.

During the preparation of this manuscript, the authors used Chat GPT (OpenAI) for linguistic refinement, structural improvement, and enhancement of academic style. All conceptual interpretations, scientific analyses, and conclusions were developed and verified by the authors.

References

Álvarez-Martínez, J. M., Nikolić Lugonja, T., Valdés, A., et al. (2026). Four decades of remote sensing for monitoring terrestrial ecosystems: A global review and future challenges. *Science of Remote Sensing, 13*, 100381. https://doi.org/10.1016/j.srs.2025.100341

Boori, M. S., Choudhary, K., Kupriyanov, A., & Kovelskiy, V. (2021). Ecosystem monitoring and ecological vulnerability assessment using geospatial technologies. *Ecological Informatics, 63*, 101318. https://doi.org/10.1016/j.ecoinf.2021.101318

Dugal, L., Thomas, L., Meenakshisundaram, A. et al. (2023) Distinct coral reef habitat communities characterized by environmental DNA metabarcoding. *Coral Reefs* 42, 17–30. https://doi.org/10.1007/s00338-022-02301-3

Dugal, L., Thomas, L., Wilkinson, S.P., Richards, Z.T., Alexander, J.B., Adam, A.A.S., Kennington, W.J., Jarman, S., Ryan, N.M., Bunce, M. and Gilmour, J.P. (2022), Coral monitoring in northwest Australia with environmental DNA metabarcoding using a curated reference database for optimized detection. Environmental DNA, 4: 63-76. https://doi.org/10.1002/edn3.199

Estoque, R. C., & Murayama, Y. (2017). Monitoring surface urban heat island formation in a tropical mountain city using Landsat data (1987–2015). *ISPRS Journal of Photogrammetry and Remote Sensing, 133*, 18–29. https://doi.org/10.1016/j.isprsjprs.2017.09.008

Gaivão, I., Santos, R. A., Morozova, T. V., & Tkach, V. V. (2025). Biological and behavioural effects of bisphenol A (BPA) exposure: An *in vivo* study in *Drosophila melanogaster*. *Applied Sciences, 15*(10), 5588. https://doi.org/10.3390/app15105588

Gerasymenko, O., Bohachova, O., & Mokriakova, M. (2025). *Lichen-indicative assessment of the ecological state of atmospheric air in urbanised areas of Eastern Ukraine*. Environmental Problems, 10(1), 55–61. https://doi.org/10.23939/ep2025.01.055

Grytsenko, A., Tykha, I., Zinchenko, I., Babich, O., & Yermakovych, I. (2024). *Decontamination of biological agents in wastewater through synergetic oxidative methods as an effective approach for safeguarding public health and aquatic ecosystems*. Chemistry & Chemical Technology, 18(3), 426-435. https://doi.org/10.23939/chcht18.03.426

Hasan, M. F. (2024). Integration of GIS and remote sensing for environmental monitoring: A systematic literature review. *International Journal of Research and Applied Technology, 4*(2), 379-385. https://doi.org/10.34010/injuratech.v4i2

Hwang, S.-O., Han, B.-H., Kim, H.-G., & Kim, B.-H. (2025). Next-generation river health monitoring: Integrating AI, GIS, and eDNA for real-time and biodiversity-driven assessment. *Hydrobiology, 4*(3), 19. https://doi.org/10.3390/hydrobiology4030019

Nahurskyi, N., Malovanyy, M., Bordun, I., & Szymczykiewicz, E. (2024). Magnetically sensitive carbon-based nanocomposites for the removal of dyes and heavy metals from wastewater: A review. *Chemistry & Chemical Technology*, *18*(2), 170–186. https://doi.org/10.23939/chcht18.02.170

Javan, F. D., Samadzadegan, F., & Toosi, A. (2025). Air pollution observation bridging spaceborne to unmanned airborne remote sensing: A systematic review and meta-analysis. *Air Quality, Atmosphere & Health*, *18*, 2481–2549. https://doi.org/10.1007/s11869-025-01771-y

Jodhani, K., Bhatiya, L., Sirvi, L., Chanda, A., Thakkar, S., & Rathnayake, U. (2026). Artificial intelligence and remote sensing frameworks for wildfire monitoring and risk analysis across multiple ecosystems: A review. *AIMS Environmental Science, 13*(1), 56-98. https://doi.org/10.3934/environsci.2026004

Li, J., Pei, Y., Zhao, S., Xiao, R., Sang, X., & Zhang, C. (2020). A review of remote sensing for environmental monitoring in China. *Remote Sensing, 12*(7), 1130. https://doi.org/10.3390/rs12071130

Lindenmayer, D. B., & Likens, G. E. (2010). The science and application of ecological monitoring. *Biological Conservation, 143*(6), 1317–1328. https://doi.org/10.1016/j.biocon.2010.02.013

Markert, B., Breure, T., & Zechmeister, H. (2003). *Bioindicators and biomonitors: Principles, concepts and applications*. Elsevier.

Mudrak, O., Morozova, T., Mudrak, H., Semeniv, V., & Symochko, L. (2025). Nectar-producing plants and crop rotation: Impacts on pollinators and yield in Hadyach UTC, Ukraine. *Journal of Environmental Problems*, *10*(4), 335–343. https://doi.org/10.23939/ep2025.04.335

Rocha, J. C., Peterson, G., Bodin, Ö., & Levin, S. (2021). Cascading regime shifts within and across scales. *Science*, *362*(6421), 1379–1383. https://doi.org/10.1126/science.aat7850

Rudenko, S. S., Morozova, T. V., Kostyshyn, S. S., Bezrukov, V. F., & Gorova, A. (2002). Micronuclear index of somatic cells in the population of Chernivtsi region and its ecological conditionality. *Cytology and Genetics*, *36*(4), 23–29.

Ruppert, K. M., Kline, R. J., & Rahman, M. S. (2019). Past, present, and future perspectives of environmental DNA (eDNA) metabarcoding: A systematic review. *Global Ecology and Conservation, 17*, e00547. https://doi.org/10.1016/j.gecco.2019.e00547

Soubry, I., Doan, T., Chu, T., & Guo, X. (2021). A systematic review on the integration of remote sensing and GIS to forest and grassland ecosystem health attributes, indicators, and measures. *Remote Sensing, 13*(16), 3262. https://doi.org/10.3390/rs13163262

Shomko, O., & Davydova, I. (2024). Assessment of forest vegetation potential of reclaimed areas after ilmenite mining using the remote earth sensing method. *Environmental Problems, 9(1),* 14-20. https://doi.org/10.23939/ep2024.01.014

Tkach, V., Morozova, T., Martins, J. I. F. P., Gaivão, I. O. M., Ivanushko, Y., Türkmenoğlu, M., & Yagodynets, P. (2025a). Electroanalytical determination of two ACCase-inhibiting herbicides in soybean products: A theoretical insight. *Orbital: The Electronic Journal of Chemistry, 17*(3), 271–275. https://doi.org/10.17807/orbital.v17i3.22023

Tkach, V. V., Morozova, T. V., Gaivão, I. O. M., Ivanushko, Y. G., Martins, J. I. F. P., & Barros, A. N. (2025b). Advancements and challenges in sucralose determination: A comparative review of chromatographic, electrochemical, and spectrophotometric methods. *Foods, 14*(7), 1267. https://doi.org/10.3390/foods14071267

Milyukin, M., & Gorban, M. (2023). Investigation of the dispersed-phase distribution of organochlorine pesticides, polychlorinated biphenyls and polycyclic aromatic hydrocarbons in natural water systems. *Chemistry & Chemical Technology, 17*(4), 846–856. https://doi.org/10.23939/chcht17.04.846

Ullo, S. L., & Sinha, G. R. (2020). Advances in smart environment monitoring systems using IoT and sensors. *Sensors*, *20*(11), 3113. https://doi.org/10.3390/s20113113 van der Heyde, M., Bunce, M., & Nevill, P. (2022). Key factors to consider in the use of environmental DNA metabarcoding to monitor terrestrial ecological restoration. *Science of the Total Environment*, *848*, 157617. https://doi.org/10.1016/j.scitotenv.2022.157617

Yoon, H. J., Seo, J. H., Shin, S. H., Abdelhamid, M. A. A., & Pack, S. P. (2025). Bioinformation and monitoring technology for environmental DNA analysis: A review. *Biosensors*, *15*(8), 494. https://doi.org/10.3390/bios15080494

Zhang, C., Wang, K., Yue, Y., Qi, X., & Zhang, M. (2023). Assessing regional ecosystem conditions using geospatial techniques: A review. *Sensors, 23*(8), 4101. https://doi.org/10.3390/s23084101