



From mapping to modeling: Spatial statistics in ethnobotanical research

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Research

Abstract

Background: Ethnobotany is a critical repository of biocultural knowledge, essential for understanding human-environment interactions. While traditional ecological knowledge (TEK) increasingly guides advanced scientific domains, like providing blueprints for sustainable nano-materials, its integration into spatial and statistical analytics remains fragmented. Historically reliant on qualitative ethnography, this methodological gap limits the discipline's capacity to support predictive conservation, spatial decision-making, and policy design under accelerating environmental change.

Methods: A systematic literature review was conducted using the Scopus database, strictly following the PRISMA protocol. A screening of 336 initial records evaluated peer-reviewed articles at the intersection of indigenous knowledge, geographic information systems (GIS), and spatial statistics. Data were extracted to identify publication trends, methodological classifications, and research gaps.

Results: The screening yielded 101 eligible articles. The synthesis reveals a clear dominance of GIS applications focused on descriptive cartography (93 papers). Conversely, advanced spatial statistical tools, such as Geographically Weighted Regression (GWR), geographic detectors, and predictive modeling, are scarce and were successfully applied in only 8 studies. This exposes an analytical deficit and a lack of predictive socio-spatial modeling in current literature.

Conclusions: This study bridges ethnobotanical knowledge systems with spatial analytical frameworks. Drawing parallels from successful adoptions in material sciences and urban sustainability, we propose a transition from descriptive mapping to inferential analytics. A future research agenda leveraging Geospatial Artificial Intelligence (GeoAI) is outlined to improve the statistical rigor of ethnobotany and provide data-driven support for biocultural conservation.

Keywords: Ethnobotany; Indigenous Knowledge; Spatial Analysis; Spatial Statistics; Systematic Literature Review; GeoAI

Background

Ethnobotany operates at the nexus of human culture and natural ecosystems by systematically documenting how indigenous and local communities utilize and manage botanical resources (Dwivedi *et al.* 2020). For decades, the discipline has captured ecological adaptations that are deeply embedded within traditional practices. This indigenous knowledge is increasingly recognized as a foundational framework capable of informing modern scientific methodologies.

The convergence of ethnobotanical knowledge with exact sciences is an established pathway to sustainable innovation. In material physics, ethnobotanical insights directly guide the selection of plant species for the green synthesis of nanoparticles (Solo *et al.* 2025). Building upon this modernization trajectory, recent bibliometric analyses highlight the necessity to integrate statistical, mathematical, and data science approaches into ethnobotany to elevate the discipline's analytical rigor (Limba *et al.* 2026). Traditional ecological knowledge has already provided empirical foundations for quantitative modeling and sustainable physics, and it holds similar potential to enhance advanced geospatial analytics.

A methodological imbalance currently exists in the field. From a socio-spatial perspective, ethnobotanical knowledge represents a form of embedded spatial cognition. Existing studies, however, rarely operationalize this cognition into measurable spatial relationships. While fields like environmental modeling and land-use science actively assimilate complex data to forecast ecological impacts (Tilly *et al.* 2024, Yang *et al.* 2021), spatial ecology within ethnobotany often relies on traditional descriptive methods. Research frequently utilizes qualitative botanical inventories and cultural significance indices. These foundational approaches lack the spatial-statistical integration required to model complex environmental interactions or analyze behavioral patterns across different landscapes.

The adoption of Geographic Information Systems (GIS) initiated a shift in how ethnobotanical data is visualized by transitioning from textual descriptions to the point-mapping of culturally significant flora (Dwivedi *et al.* 2020). Recent advancements have also begun addressing geographic feasibility by introducing indices like the Spatial Availability Score (SAS) to evaluate the spatial dimensions of plant utility (Nazari & Bussmann 2026). Yet, mapping alone remains analytically limited. In broader landscape management, spatial statistical modeling that quantifies spatial dependencies and heterogeneity is standard practice. Methods such as spatial autocorrelation and Geographically Weighted Regression (GWR) have significantly improved the understanding of land-use dynamics (Yigitcanlar & Kamruzzaman. 2014, Yigitcanlar. 2022). Despite this utility, advanced spatial methodologies remain underutilized in ethnobotany, where spatial data is often treated as an end-product rather than as an independent variable for statistical inquiry.

This study moves beyond conventional ethnobotanical reviews by positioning spatial analysis as a pathway towards predictive modeling in indigenous knowledge systems. Inspired by PRISMA reviews in related sustainability fields (Tilly *et al.* 2024), this study aims to: (1) systematically map the current landscape of spatial methods in ethnobotany, (2) quantify the deficit of advanced spatial statistics, and (3) propose a conceptual framework that integrates predictive spatial modeling into biocultural conservation.

Materials and Methods

This systematic literature review was designed to capture the interdisciplinary intersection of ethnobotany and computational geography. The methodology adheres to the Preferred Reporting Items for Systematic Reviews and Meta Analyses (PRISMA) protocol to ensure transparency and analytical rigor (Tilly *et al.* 2024).

Data Source and Search Strategy

Data extraction was executed using the Scopus database, which was selected for its comprehensive indexing of peer-reviewed literature across environmental, biological, and social sciences. To avoid disciplinary bias, the search strategy utilized a structured Boolean concept-block approach (detailed fully in Appendix A). The query intersected three primary domains: cultural paradigms, resource focus, and spatial methodologies. Limits were applied to include only peer-reviewed, English-language research articles, excluding gray literature and unverified conference abstracts.

Screening Process and Quality Appraisal

The screening and selection followed a multi-stage PRISMA workflow (Fig. 1). The initial database query identified 336 records. Utilizing algorithmic deduplication followed by manual verification, 20 duplicates were removed. The remaining 316 papers underwent title and abstract screening, resulting in the exclusion of 40 articles that were out of scope.

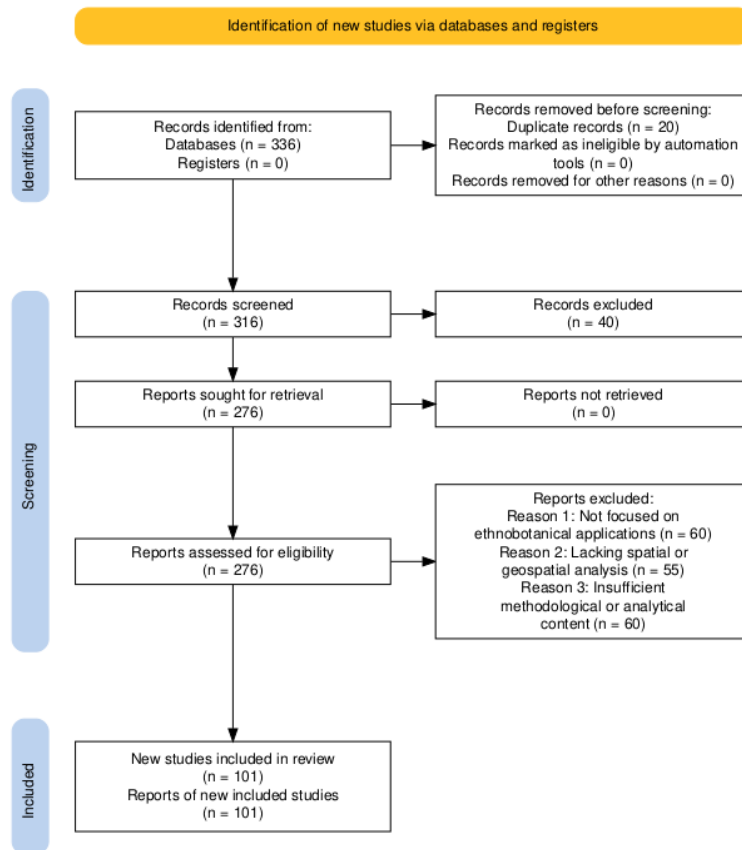


Figure 1. PRISMA flow diagram detailing the systematic screening process of ethnobotanical and spatial literature.

The remaining 276 full-text articles were rigorously assessed against predefined inclusion criteria. This study employed a custom spatial rigor scoring system (detailed in Appendix B) to objectively appraise the methodological depth of each paper. This evaluation led to the exclusion of 175 articles, primarily due to weak methodological frameworks such as studies utilizing generic commercial maps without conducting primary spatial data processing. A final cohort of 101 papers was established for systematic synthesis.

Results

Publication Trends and Bibliometric Overview

The chronological distribution of the 101 included articles reveals an upward trajectory with a notable acceleration in publications post-2018 (Fig. 2). A comprehensive summary of the dataset's bibliometric characteristics is provided in Table 1.

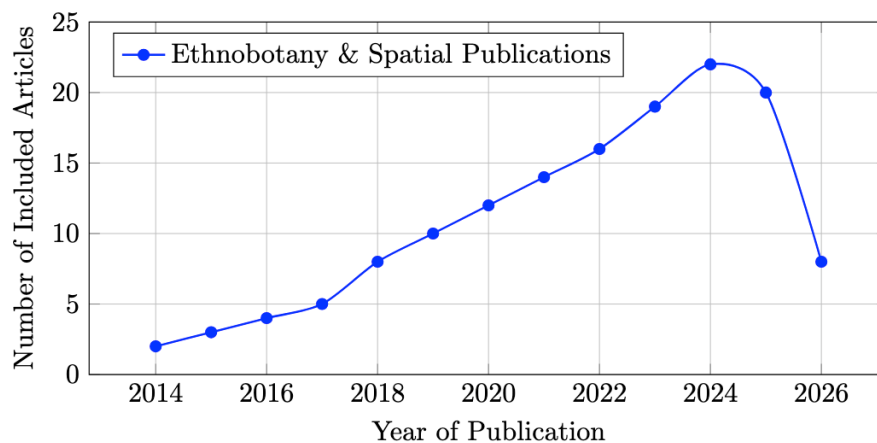


Figure 2. Annual distribution of the 101 selected publications.

While basic spatial approaches provide foundational insights, such as using GIS to document the spatial pattern of traditional villages (Cao & Kim. 2025), they lack the predictive capacity required for dynamic biocultural conservation management.

Insights from the Advanced Spatial-Statistical Subset

The small subset of 8 advanced papers provides a functional template for the discipline by demonstrating how integrating robust statistics transforms qualitative ethnobotanical data into actionable intelligence (a full synthesis is provided in Appendix D).

Recent advancements highlight the deployment of predictive and inferential algorithms across diverse biocultural domains. In the context of threat and depletion modeling, maximum entropy (MaxEnt) algorithms have been utilized to identify drivers and hotspots of illegal hunting by explicitly integrating the local spatial knowledge of park rangers (dos Santos Sampaio *et al.* 2026). By mapping variables such as altitude and proximity to rivers, the study successfully translated qualitative field observations into high-priority monitoring zones. Similarly, in the domain of biocultural conservation, researchers have applied Geographically Weighted Regression (GWR) to analyze over 3,800 medicinal plants. This approach quantitatively demonstrated how socioeconomic and environmental variables significantly influence the spatial distribution of phylogenetic diversity (Hao *et al.* 2026).

Advanced spatial applications are bridging disciplines by combining computational geography with cultural data. Geographic detectors and 2.5D spatial analysis have been applied to explore the structural differentiation of traditional villages, revealing patterns of cultural agglomeration and spatial clustering (Ge *et al.* 2024, Liu *et al.* 2025, Zhang *et al.* 2025). In environmental hazard contexts, researchers have integrated multi-layer hydrological modeling with participatory validation to identify vulnerability hotspots (Li *et al.* 2025), and crossed participatory mapping with historical geographic information to track environmental exposures (Lysaniuk *et al.* 2020). These studies confirm that applying robust spatial statistics to traditional knowledge yields high-resolution empirical insights.

Discussion

The findings reveal a structural methodological imbalance. Ethnobotany offers rich qualitative depth but currently remains limited in quantitative spatial frameworks. This stagnation likely stems from several intersecting factors. Historically, ethnobotany has been rooted in descriptive anthropology and taxonomic biology, disciplines that traditionally prioritize qualitative narratives over spatial econometrics. Additionally, there is an inherent epistemological challenge in quantifying indigenous knowledge. Cultural values, sacred geographies, and traditional foraging behaviors are highly abstract and often resist simple translation into numerical variables suitable for statistical modeling. Finally, a lack of interdisciplinary training in advanced spatial software and machine learning within standard ethnobotanical curricula perpetuates the reliance on basic point-mapping.

Consequently, the current trajectory risks confining the discipline to a descriptive archive and limiting its advancement as a predictive analytical science. In contrast to broader environmental modeling and ecological forecasting where spatial statistics are fundamental for predicting ecosystem dynamics (Yang *et al.* 2020, 2021), ethnobotany remains methodologically conservative. Relying solely on descriptive mapping restricts researchers to a documentary role, often recording knowledge erosion or resource depletion only after it has occurred. Without integrating spatial-statistical frameworks, ethnobotany will face challenges in contributing to predictive sustainability science or informing proactive climate adaptation policies.

The emergence of techniques like geographic detectors (Ge *et al.* 2024) and spatial phylogenetics (Hao *et al.* 2026) within the advanced subset proves that overcoming this limitation is possible. By mapping phylogenetic and geographic resilience, researchers can bridge biocultural diversity with actionable environmental policy (Hao *et al.* 2026).

Conceptual Framework for Spatial Intelligence in Ethnobotany

To address the identified methodological gap, this study proposes a conceptual framework that integrates indigenous knowledge systems with robust spatial and statistical analytical layers (Fig. 4).

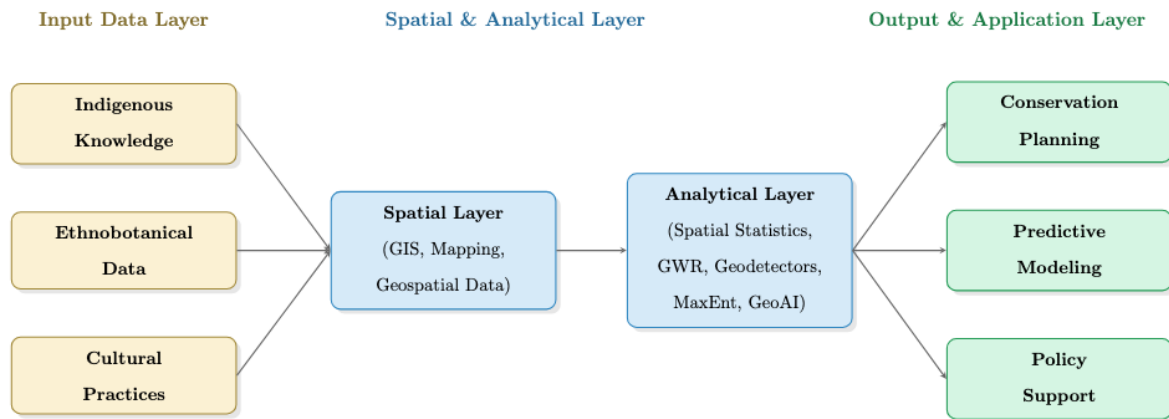


Figure 4. Conceptual framework for integrating indigenous knowledge with spatial and statistical analytics in ethnobotanical research.

The framework conceptualizes ethnobotanical knowledge not merely as descriptive cultural information, but as spatially embedded data that can be transformed into analytical inputs. Through the integration of GIS-based spatial representation and statistical modeling, ethnobotanical data is translated into predictive and policy-relevant outputs. This transformation enables a shift from descriptive documentation towards advanced spatial understanding, supporting conservation planning and resource management.

To mathematically formalize this analytical layer, we advocate for the transition from global statistical models to local spatial estimators, such as Geographically Weighted Regression (GWR) (Hao *et al.* 2026). In an ethnobotanical context, the biocultural variable at a specific indigenous geographic location (u_i, v_i) can be modeled as:

$$y_i = \beta_0(u_i, v_i) + \sum_{k=1}^p \beta_k(u_i, v_i)x_{ik} + \epsilon_i,$$

where y_i represents the dependent ethnobotanical variable (e.g., harvesting intensity, cultural significance index, or medicinal species diversity), x_{ik} represents environmental or socio-economic predictors, and $\beta_k(u_i, v_i)$ denotes the continuous spatial coefficient functions that vary across the landscape. Explicitly incorporating such equations allows researchers to quantify how traditional behaviors and ecological interactions shift across different ecotones, officially moving the discipline from descriptive cartography into inferential spatial science.

Just as indigenous knowledge of plant properties guides the synthesis of nanotechnology (Solo *et al.* 2025), indigenous observations of ecological phenology and land use can guide feature selection in spatial machine learning and predictive algorithms.

Conclusion and Future Directions

This review critically evaluated the state of spatial methodologies within ethnobotanical research. This study provides quantitative evidence of a structural methodological gap in ethnobotany by highlighting the underutilization of spatial statistical approaches. Through a PRISMA analysis of 101 studies, we identified that 92% of the literature relies entirely on descriptive GIS mapping, with inferential spatial statistics appearing in only 8% of the reviewed corpus.

To improve the discipline's analytical capacity, future research should transition from retroactive documentation to predictive socio-spatial modeling. The successful application of Geographically Weighted Regression (GWR), geographic detectors, and MaxEnt in a minority of studies provides a clear methodological roadmap. Moving forward, leveraging Geospatial Artificial Intelligence (GeoAI) offers a powerful avenue to analyze complex ethnobotanical datasets and identify biocultural risk hotspots before they erode. Improving the statistical rigor of ethnobotany is a necessary evolution to ensure the discipline provides robust, data-driven support for global biodiversity conservation.

Declarations

List of abbreviations: GIS - Geographic Information Systems; GWR - Geographically Weighted Regression; PRISMA - Preferred Reporting Items for Systematic Reviews and Meta-Analyses; GeoAI - Geospatial Artificial Intelligence; MaxEnt - Maximum Entropy.

Ethics approval and consent to participate: Not applicable. This study is a systematic literature review and did not involve human or animal subjects.

Consent for publication: Not applicable

Availability of data and materials: All data generated or analyzed during this study are included in this published article and its appendices.

Competing interests: The authors declare that they have no competing interests.

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Author contributions: M.A.I. conceptualized the study, performed data curation, formal analysis, and wrote the original draft. A.A.Y., M.N.H.T.P., and R.A. assisted in the methodology, spatial software validation, and critical review. N.S., F.F., I.S., Z.M., and U.D.A.R. contributed to the literature screening, quality appraisal, and editing of the manuscript. All authors read and approved the final manuscript.

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Appendix

Appendix A. Comprehensive Search Protocol and Query Design

To ensure methodological transparency and replicability, the search strategy was constructed using a concept-block approach. The Scopus database was selected due to its extensive indexing of interdisciplinary environmental, geographical, and social science journals. The final query was executed on April 21, 2026.

Table A1. Boolean Concept Blocks Used for Database Query

Conceptual Block	Keywords and Search Terms
Domain 1: Cultural Paradigm	"ethnobotan*" OR "traditional knowledge" OR "indigenous knowledge" OR "traditional ecological knowledge" OR "biocultural"
Domain 2: Resource Focus	"plant*" OR "flora" OR "medicinal" OR "foraging" OR "harvesting"
Domain 3: Spatial Methodology	"spatial" OR "GIS" OR "mapping" OR "geographic information system" OR "spatial statistics" OR "spatial autocorrelation" OR "geographically weighted regression" OR "Moran's I" OR "hotspot"
Applied Filters	DOCTYPE: "ar" (Article); LANGUAGE: "English"

Final Executed String: TITLE-ABS-KEY(Domain 1 AND Domain 2 AND Domain 3) AND LIMIT-TO (DOCTYPE, "ar") AND LIMIT-TO (LANGUAGE, "English")

Appendix B. Standardized Data Extraction and Spatial Rigor Appraisal

During the full-text assessment of the 101 included articles, a standardized matrix was utilized not only to extract bibliometric data but to objectively evaluate the methodological depth of each paper. The classification detailed in Section 3.2 was directly derived from this scoring system.

Table B1. Spatial Rigor Scoring System Applied for Classification

Level	Classification	Methodological Criteria for Appraisal	Literature Examples
1	Basic Visualization	Utilization of GIS strictly for point plotting (e.g., identifying coordinates of plant collection) without geoprocessing.	Majority of subset (n =93)
2	Geoprocessing	Application of descriptive spatial tools such as buffer zones or spatial overlays to calculate area.	Cao & Kim. 2025
3	Inferential Statistics	Use of geographic detectors, clustering, or spatial regressions (e.g., GWR) to test hypotheses and determine significance.	Hao <i>et al.</i> 2026; Ge <i>et al.</i> 2024
4	Predictive Modeling	Implementation of algorithms (e.g., MaxEnt, Machine Learning) to forecast spatial distributions under varying scenarios.	dos Santos Sampaio <i>et al.</i> 2026

Appendix C. Cross-Disciplinary Translation Matrix

To operationalize the conceptual framework presented in Section 4.1, Table C1 translates advanced methodologies from spatial ecology and environmental management (Yigitcanlar & Kamruzzaman 2014, Yang *et al.* 2021) into practical applications for ethnobotanical research.

Table C1. Translating Spatial Analytics into Biocultural Models

Methodology (Source Discipline)	Proposed Operationalization in Ethnobotany
Demand Frameworks (Yang <i>et al.</i> 2020) (Resource Economics)	Harvesting Pressure Analysis: Modeling the spatial demand, economic constraints, and travel behavior of traditional harvesters under conditions of resource scarcity.
Spatial Self-Containment (Yigitcanlar & Kamruzzaman 2014) (Land-Use Planning)	Biocultural Radius Modeling: Analyzing the spatial limits, geographic accessibility, and containment of traditional foraging zones radiating from indigenous settlements.

Life Cycle Assessment (Yang <i>et al.</i> 2021) (<i>Industrial Ecology</i>)	Biocultural Life Cycle Assessment: Quantifying the long term spatial ecological footprint and depletion rates resulting from the transition of traditional medicinal plants into global commercial supply chains.
Network Connectivity (<i>Spatial Informatics</i>)	Knowledge Transmission Networks: Using spatial graph theory to model how traditional ecological knowledge transfers geographically between neighboring communities or across linguistic boundaries.

Appendix D. Synthesis of the Advanced Spatial-Statistical Subset

To provide a clear roadmap for advancing ethnobotanical research, Table D1 summarizes the core methodologies and findings of the 8 advanced papers identified in this systematic review. These studies demonstrate the successful integration of traditional knowledge with robust inferential and predictive spatial statistics.

Table D1. Methodological Synthesis of the 8 Advanced Spatial-Statistical Studies

Authors (Year)	Analytical Domain	Methodology and Core Findings
Dos Santos Sampalo <i>et al.</i> 2026	Threat and Depletion Modeling	<ul style="list-style-type: none"> Integrated local ranger knowledge with MaxEnt spatial modeling. Identified altitude, proximity to rivers, and forest cover as main drivers of illegal hunting.
Hao <i>et al.</i> 2026	Spatial Phylogenetics and Biocultural Diversity	<ul style="list-style-type: none"> Analyzed 3,833 minor ethnomedicine plants using spatial endemism and phylogenetic diversity metrics. Applied Geographically Weighted Regression (GWR) to determine that socioeconomic and environmental variables significantly influence medicinal plant diversity.
Liu <i>et al.</i> 2025	Traditional Settlement Morphology	<ul style="list-style-type: none"> Synthesized representational theory with urban morphology theory using 2.5D spatial analysis. Revealed significant spatial patterns of cultural agglomeration, similarity, and continuity.
Cao & Kim 2025	Settlement Pattern Distribution	<ul style="list-style-type: none"> Applied quantitative geography and GIS to analyze the spatial distribution characteristics of traditional villages. Demonstrated that settlements cluster based on the natural geographic environment and historical human factors.
Li <i>et al.</i> 2025	Epidemiological and Hazard Modeling	<ul style="list-style-type: none"> Developed a GIS-based spatial risk map integrating multi-layer hydrological modeling to assess mining induced water hazards. Translated indigenous knowledge into spatially referenced mitigation plans via participatory validation.
Zhang <i>et al.</i> 2025	Ecological Space Pattern Identification	<ul style="list-style-type: none"> Constructed a research path analyzing spatial distribution to identify Production-Living-Ecological space pattern languages. Identified five distinct spatial pattern languages reflecting cultural and ecological integration.
Ge <i>et al.</i> 2024	Spatial and Cultural Differentiation	<ul style="list-style-type: none"> Utilized multi-factor geographic detectors and cultural geography spatial zoning methods. Quantified correlations between economic levels (GDP), distance to roads, and traditional settlement preservation.
Lysaniuk <i>et al.</i> 2020	Historical Exposure and Participatory GIS	<ul style="list-style-type: none"> Crossed participatory mapping with historical topographic maps and aerial photographs. Geographically located underground asbestos contamination zones that posed significant environmental exposure risks.