Yakubu Yuguda [2024]. International Journal of Medical Justice, IJMJ, Volume 2, Issue 2: July-December 2024 [E-ISSN: 2583-7958]
International ISSN [CIEPS]: 3006-208X[Print] 3006-2098[Online]
Content list Available at ijmj.net

International Journal of Medical Justice

Journal Homepage: https://www.ijmj.net

Review Article:

Recent Advances in Forensic Techniques for Ecosystem Analysis: A review

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Article History:

Date of Submission: Sunday August 25, 2024.

Date of Start of Review Process: Wednesday September 04, 2024

Date of Receipt of Reviewers Report: Sunday October 13, 2024.

Date of Revision: Wednesday October 23, 2024.

Date of Acceptance: Wednesday October 23, 2024

Date of Publication: Tuesday December 10, 2024

Digital Object Identifier **[DOI]**: 10.5281/zenodo.14254136

Available Online: Tuesday December 24, 2024

Website Archive: https://www.ijmj.net/archive/2024/2/IJMJ-2024-223.pdf

Citation: 1. Yakubu Magaji Yuguda. Recent Advances in Forensic Techniques for Ecosystem Analysis: A review. International Journal of Medical Justice. 2024 Dec10;2(2):83-92.

Indexing: OpenAIRE, INTERNATIONAL Scientific Indexing, LetPub INDEX COPERNICUS INTERNATIONAL

Keywords:

Academic Editor: Dr. Senthil Kumaran M

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Abstract: The vitality of our planet is fundamentally reliant on ecosystems, which represent complex interrelated systems. Nevertheless, due to anthropogenic actions and alterations in the environment, these systems encounter numerous threats and challenges. This paper scrutinizes the most contemporary advancements in forensic methodologies employed in the analysis of ecosystems. This review article investigates cutting-edge techniques including Geographic Information Systems (GIS) and remote sensing, stable isotope ecology, environmental DNA (eDNA) analysis, machine learning, forensic palynology and plant science, bioinformatics and big data analytics, modeling and three-dimensional printing, chemical fingerprinting, Light Detection and Ranging (LiDAR), forensic entomology, sensor networks and the Internet of Things (IoT), hyperspectral imaging, DNA barcoding, artificial intelligence (AI) and machine learning applications, acoustic monitoring, and the analysis of micro and nano plastics. By adopting and integrating these innovative methodologies, the ecosystem can be substantially enhanced, ecological degradation can be mitigated, and a more sustainable coexistence with the natural world can be fostered.

Keywords: Forensic Techniques, Ecosystem, Forensic Science, Environmental Change, Human Activity, Ecosystem Analysis.

Introduction: Ecosystems provide a multitude of ecological, economic, and social benefits, serving as the essential life-sustaining networks of our planet. However, issues such as habitat destruction, pollution, climate change, and the loss of biodiversity exert continuous pressure on these intricate systems. The maintenance of ecological balance and the perpetuation of life on Earth are contingent upon ecosystems, which comprise a diverse array of habitats. They render ecological services including climate regulation, biodiversity maintenance, and the provision of clean water and air. Environmental challenges instigated by human activities encompass deforestation, habitat degradation, and the introduction of non-native species [15].

Researchers are increasingly employing forensic methodologies, traditionally utilized in criminal investigations, to enhance the understanding, preservation, and management of ecosystems. These avant-garde techniques afford scholars a profound comprehension of and safeguarding for ecosystems and have proven to be exceedingly beneficial in the domain of ecosystem analysis for the detection of environmental crimes, assessment of ecological harm, and formulation of effective conservation strategies [10]. Progressions in forensic techniques pertinent to ecosystem analysis have markedly augmented our capacity to investigate and comprehend environmental offenses, scrutinize ecological systems, and monitor environmental health. These methodologies are vital for confronting challenges such as illegal logging, poaching, pollution, and habitat degradation. This review article delineates the most recent advancements in forensic techniques for ecosystem analysis and elucidates how these strategies empower researchers to effectively investigate, safeguard, and conserve ecosystems.

2. Some Key Advances in Forensic Techniques for Ecosystem Analysis

2.1 Geographic Information Systems (GIS) and Remote Sensing

The field of ecosystem analysis has undergone significant transformations due to advancements in technologies associated with Geographic Information Systems (GIS) and remote sensing methodologies. Researchers are now equipped to collect and scrutinize data pertaining to ecological parameters, including vegetation composition, water quality metrics, land cover classification, and land utilization patterns through the application of these sophisticated technologies. High-resolution datasets, essential for the monitoring and management of ecosystems, can be procured via the utilization of drones, aerial surveys, and cutting-edge satellite imaging techniques. The application of remote sensing instruments facilitates the precise targeting of conservation initiatives through habitat assessments, deforestation identification, and the analysis of landscape alterations.

2.2 Analysis of Stable Isotopes

This potent forensic methodology elucidates an organism's nutritional preferences, migratory behaviors, and favored habitats. By scrutinizing the stable isotopic ratios of elements including carbon, nitrogen, and oxygen within animal tissues, researchers are able to deduce an individual's trophic level, geographical provenance, and ambient environmental conditions [4]. The understanding of pollutant pathways, identification of environmental toxin sources, and the exploration of food web dynamics are all contingent upon this critical information.

2.3 Using Environmental DNA (eDNA) for Ecosystem Analysis

Environmental DNA (eDNA) analysis represents an advanced methodological approach in the examination of ecosystems. This process involves the extraction and subsequent analysis of genetic material present in the environment. In order to ascertain the species that have contributed genetic material, researchers collect samples of air, soil, or water from various habitats and employ DNA sequencing techniques. This non-invasive methodology facilitates the tracking of invasive species and the monitoring of species presence or absence across different ecosystems, thereby contributing to the conservation of endangered species. In the assessment of aquatic ecosystem health and the identification of illegal wildlife trafficking activities, eDNA analysis has become an indispensable tool.

2.4 Forensic Palynology and Plant Science

These academic disciplines focus on the microscopic botanical particles, such as pollen, spores, and various plant structures, which are scrutinized during forensic investigations. Beyond their application in criminal jurisprudence, these methodologies also hold significance in the realm of environmental assessment [9]. By analyzing plant assemblages and pollen preserved within sediments, soil, or the digestive systems of fauna, researchers can reconstruct historical ecosystems, trace the evolution of plant life, and elucidate the impacts of climate change on biodiversity.

2.5 Bioinformatics and Big Data

Sophisticated bioinformatics methodologies are requisite for the management, processing, and assessment of the substantial quantities of data produced in ecological investigations. Mechanisms for environmental surveillance, satellite remote sensing, and genomic sequencing yield extensive data repositories [17]. To predict the well-being of ecosystems, the spatial distribution of biotic species, and the ramifications of anthropogenic influences on the natural world, researchers can derive significant advantages from the application of big data analytics and machine learning paradigms.

2.6 Modeling and 3D Printing

Because of advancements in these domains, scientists are now able to produce intricate physical representations of species, environments, and ecosystems. With the use of these models, scientists may analyze the effects of climate change, simulate different environmental scenarios, and create management and restoration plans for ecosystems. By predicting the effects of environmental changes on ecosystems, spatial modeling tools support the creation of management and conservation plans. They are especially useful for study on wetlands, woodlands, and coral reefs.

2.7 Chemical Fingerprinting

Chemical fingerprinting, commonly known as isotope ratio mass spectrometry, constitutes the analytical methodology employed in the investigation of chemical signatures present within various environmental matrices, including biological tissues, soil, and aqueous samples. Through the analysis of isotopic ratios for elements such as oxygen, carbon, and hydrogen, researchers are capable of detecting the presence of contaminants, tracing their dispersal throughout ecosystems, and determining their sources and origins. This methodological approach is indispensable for the management of environmental crises, the understanding of nutrient cycling processes, and the investigation of pollution events.

2.8 Light Detection and Ranging (LiDAR)

Light Detection and Ranging (LiDAR) technology employs laser emissions to create three-dimensional representations of the Earth's surface. This methodology proves exceptionally beneficial for the characterization of habitats, the execution of topographical mapping, and the investigation of forest canopy dynamics [7]. The acquisition of precise measurements regarding vegetation structure is facilitated through Light Detection and Ranging (LiDAR) data, which can subsequently be utilized to monitor deforestation trends, assess biodiversity, and identify potential sites for ecosystem conservation.

2.9 Insect forensics

Ecosystem analysis has incorporated forensic entomology, notwithstanding its predominant association with criminal investigations. By scrutinizing the insect species present within a given habitat, researchers can ascertain the existence of environmental contaminants, the chronology of faunal mortality, and even the ramifications of climate change on insect demographics. This information can facilitate a deeper comprehension of broader ecological transformations and their implications for environmental integrity.

2.10 Sensor Networks and Internet of Things (IoT)

The amalgamation of sensor networks with the Internet of Things (IoT) has been integrated into the analysis of ecological systems. These networks comprise a diverse array of sensors strategically deployed across various ecosystems to collect real-time data regarding environmental parameters such as temperature, humidity, air quality, and water quality. The implementation of IoT-driven technologies facilitates ongoing surveillance, prompt detection of environmental alterations, and rapid response to ecological threats [6].

2.11 Barcoding of DNA

The investigation of biodiversity has undergone a significant transformation through the implementation of DNA barcoding methodologies. In order to ascertain the species classification of a specimen, short, standardized sequences of DNA derived from the specimen are subjected to sequencing analysis [7]. This innovative technique has been employed to monitor the proliferation of invasive species, to identify species present in confiscated products, and to assess genetic diversity within endangered populations, all aimed at combating the illicit wildlife trade. Recent advancements in DNA barcoding have markedly enhanced the efficiency, precision, and cost-effectiveness of species identification processes. Such advancements encompass the utilization of high-throughput sequencing technologies alongside comprehensive reference databases.

2.12 Multispectral Imagery

A type of remote sensing called hyperspectral imaging collects information throughout a large portion of the electromagnetic spectrum [18]. Scientists can identify and track certain plant species, diagnose stress in vegetation, and evaluate changes in land cover by examining these spectral signatures. Because it offers comprehensive, non-invasive insights into ecosystems at different scales, hyperspectral photography has completely changed the field of ecosystem studies.

2.13 Artificial Intelligence (AI) and Machine Learning.

In ecosystem analysis, machine learning and artificial intelligence (AI) are being utilized more and more for data analysis and pattern recognition. Large datasets may be processed by them, and they can spot trends that human researchers might overlook.

2.14 Acoustic Monitoring

To identify species, gauge population densities, and track behavioral changes brought on by environmental perturbations, sophisticated acoustic monitoring devices may capture and analyze noises in ecosystems.

2.15 Examination of Micro and Nano plastics

Plastics are long lived and resistant to biodegradation, thus accumulating in the environment to a broad extent. However, it should be noted that all sizes of plastics produced and disposed of on land because of anthropogenic activities have also been extensively reported in terrestrial and adjacent freshwater environments [12]. As the issue of plastic pollution grows, sophisticated methods for locating and measuring microplastics in ecosystems have been created.

Conclusion

The field of ecosystem analysis has experienced significant innovation recently, attributable to advancements in forensic methodologies. Geographic Information Systems (GIS) and remote sensing, stable isotope ecology, environmental DNA (eDNA) analysis, machine learning, forensic palynology and botany, bioinformatics and big data, modeling and three-dimensional printing, chemical fingerprinting, Light Detection and Ranging (LiDAR), forensic entomology, sensor networks and the Internet of Things (IoT), hyperspectral imaging, DNA barcoding, artificial intelligence (AI) alongside machine learning, acoustic monitoring, and the analysis of micro and nano plastics have fundamentally transformed the understanding and capability for managing and preserving ecosystems. Through the application of these methodologies, researchers can ascertain species identity without necessitating direct observation, detect subtle ecological alterations, and predict the implications of anthropogenic activities on natural ecosystems. Given the increasing susceptibility of ecosystems to the ramifications of climate change and human interventions, the integration of these pioneering techniques is imperative for ensuring their sustained viability. By harnessing the capabilities of forensic methodologies, it is possible to foster a more sustainable coexistence with the natural environment and safeguard the diverse ecosystems that constitute the uniqueness of our planet.

In summary, the effective management of our planet's resources, the conservation of natural habitats, and the resolution of environmental challenges are all contingent upon the advancements in forensic instruments for ecosystem analysis. These methodologies equip scientists and environmentalists with enhanced insights into the complex interdependencies within ecosystems, thereby facilitating more informed decisions regarding environmental conservation and rehabilitation. Anticipated future technological developments are likely to produce even more innovative tools and resources that will assist in deepening our comprehension of nature and ensuring the sustainability of ecosystems.

Financial support and sponsorship: Nil.

Conflicts of interest: The author reports no conflicts of interest. The author alone is responsible for the content and writing of the review paper.

Acknowledgment

The author wishes to acknowledge Forensic Investigators society of Nigeria (FISN) and Security and Forensic Studies Nigeria for their endless support.

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