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Telepon: +62711-580063 Fax: +62711-581179
ISSN : 1410-0614
E-ISSN : 2684-9941
E-mail: simburcahaya@fh.unsri.ac.id
Website: http://journal.fh.unsri.ac.id/simburcahaya

Geo-Forensic Criminal Law: Strengthening Environmental Criminal Evidence in the Mining Sector Through Geospatial Technology

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Article Info

Article History:
Received : 04-03-2026
Revised : 07-06-2026
Accepted : 15-06-2026
Published : 29-06-2026

Keywords:
Geo-forensics; Environmental criminal evidence; Geospatial technology; Corporate criminal liability; Mining

DOI.
10.28946/sc.v33i1.5840

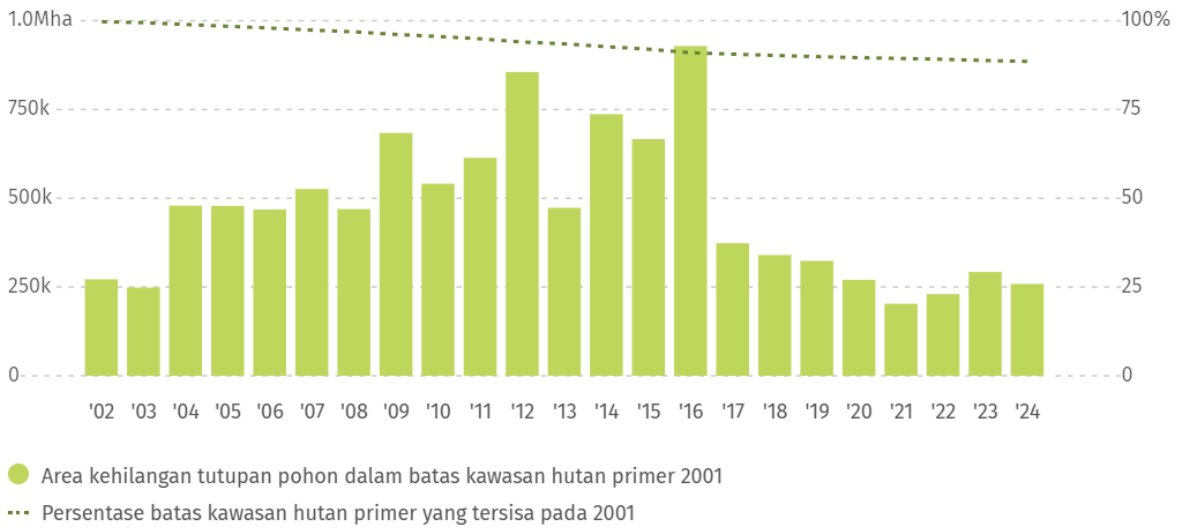
Abstract

The expansion of mining investments within the framework of national economic development is often accompanied by an increased risk of environmental damage that is difficult to prove through conventional means, especially in remote areas with complex licensing. This condition raises the issue of the effectiveness of evidence in environmental criminal law enforcement, considering that ecological crimes often occur covertly and require precise scientific analysis. This study examines the main problem of how geospatial technologies such as high-resolution satellite imagery, GIS-based mapping, LiDAR, and drone monitoring can serve as geo-forensic instruments to strengthen criminal evidence in mining cases. Using a normative research method, this study analyses the evidentiary regulatory framework in the 2009 Environmental Protection and Management Law (UU PPLH) and the scientific evidentiary standards in judicial practice. It juxtaposes them with actual case studies of mining crimes in Indonesia. The results of the study indicate that geospatial evidence has strong evidentiary value because it can present digital traces of environmental damage in real time and with traceability; however, there are still normative challenges related to data authentication, the digital chain of custody, and the capacity of law enforcement officials. This research concludes that there is a need to construct a Geo-Forensic Criminal Law as a modern evidentiary framework that integrates geospatial science into the environmental criminal evidence system to improve accuracy, effectiveness, and legal certainty in the supervision of the mining industry.

INTRODUCTION

Mining activities in Indonesia have experienced a significant surge in line with the acceleration of national development and efforts to meet the natural resource needs for both domestic industries and exports. (Rizqiani et al., 2024) Based on the official report from the Ministry of Energy and Mineral Resources (ESDM) during the Working Meeting with Commission VII of the Indonesian House of Representatives on November 12, 2024, it was recorded that the area of mining business licenses (IUP) in Indonesia reached 9,112,732 hectares, covering all phases of mining activities from exploration, production operation, post-mining, to reserve areas. Of the total, production-operation IUPs dominate, covering approximately 8.08 million hectares, comprising metal mineral commodities (±3.82 million hectares), coal (±3.98 million hectares), non-metallic minerals (±73,915 hectares), rocks (±85,520 hectares), and certain types of non-metallic minerals (±119,914 hectares). Meanwhile, exploration IUPs are recorded at an area of ±1.01 million hectares, covering metal minerals (±360,513 hectares), coal (±117,278 hectares), non-metallic minerals (±110,347 hectares), rocks (±68,733 hectares), and certain types of non-metallic minerals (±360,594 hectares). In addition, post-mining areas cover 6,685 hectares, while reserved areas only cover 91 hectares. This data shows that production operation permits constitute the largest share of national mining governance, reflecting the intensive utilisation of mineral and coal resources on a large scale, which directly contributes to challenges in environmental supervision and protection. This large production figure simultaneously presents increasingly complex environmental challenges, as extractive activities often occur in forest areas, wetlands, and remote regions with high ecological sensitivity.

Figure 1. Loss of Primary Forest in Indonesia



Sumber: globalforestwatch.org

Environmental damage resulting from mining has been demonstrated spatially and quantitatively. For example, analysis of Global Forest Watch (GFW) data shows that Indonesia has experienced significant loss of wet primary forest cover over the last two decades. During 2002–2024, the total loss of wet primary forest amounted to approximately 11 million hectares, or 34% of the national tree cover loss, and the area of primary forest declined by 11% relative to the 2001 baseline. Overall, Indonesia's tree cover loss from 2001–2024 totalled 32 million hectares, equivalent to 20% of its 2000 tree cover, and resulted in 23 gigatons of CO_2e emissions into the atmosphere. If viewed in terms of driving factors, 76% of tree cover loss is caused by permanent deforestation, primarily due to plantation expansion, settled agriculture, and infrastructure development, which are generally closely related to access to mining resources and to land clearing for industrial-scale mining activities.(*Indonesia Deforestation Rates & Statistics | GFW*, n.d.) In addition to deforestation and greenhouse gas emissions, mining activities contribute to land degradation, land-cover change, water and air pollution, habitat destruction, and socio-ecological conflicts with local communities.

On the legal and enforcement side, the mining sector in Indonesia faces serious obstacles to the effective prosecution of environmental crimes. Environmental damage in mining projects often occurs covertly, lasts for a long time, and involves technical complexities and difficult-to-access

locations. As a result, law enforcement agencies and regulatory bodies face limitations in obtaining scientifically sound evidence to meet the burden of proof in criminal proceedings. Moreover, national environmental and mining regulations indicate that evidence management still relies on traditional mechanisms such as AMDAL documents, field inspections, and company reporting. At the same time, advancements in geospatial technology have not yet been optimally utilised as environmental forensic instruments.

Advances in geospatial technology, including high-resolution satellite imagery, Geographic Information System (GIS)-based mapping, LiDAR, drone monitoring, and temporal analysis of land-cover changes, offer new opportunities to demonstrate environmental damage caused by mining.(Lamb, 2000). Research on land degradation from small-scale gold mining, for example, has used remote sensing as an objective, spatial method for modelling environmental damage. However, the integration of this technology into the environmental criminal evidence system remains limited on the normative (legal rules), institutional (law enforcement capacity), and operational (digital evidence authentication, chain of custody, technical validation) sides.

In this context, there is an urgent need to formulate an environmental criminal evidence model that systematically employs geospatial technology, which I refer to as Geo-Forensic Criminal Law. This model must accommodate the characteristics of mining-induced environmental damage: large areas, widespread damage, digital/spatial evidence sources, and rapid temporal dynamics. This includes aspects such as identifying damage footprints using satellite imagery, mapping land-use changes, assessing the spatial relationship between mining activities and environmental damage, and documenting digital evidence that can be used in criminal proceedings. In practice, this requires alignment between environmental criminal law regulations in Indonesia, such as Law Number 32 of 2009 on Environmental Protection and Management (Environmental Law), and valid and credible geospatial technical methodologies.(Siregar & Zul, 2015)

Furthermore, the existence of mining conflicts between local communities and mining companies reinforces the urgency of demonstrating superior technical capabilities. A study on mining conflicts across various regions of Indonesia found that communities largely reject mining activities due to perceived environmental damage, including landslides, dust pollution, road damage, and declining water quality. At the same time, companies are seen as neglecting environmental and social aspects of their operations. This emphasises that strong evidence is not merely about formal permits, but also about tangible evidence of environmental damage that can

be measured and scientifically reconstructed, so that criminal accountability can be enforced effectively and fairly.

On the other hand, concrete cases illustrate how unauthorised or excessive mining activities can cause significant environmental damage and pose challenges for law enforcement. In Bangka Belitung Province, illegal tin mining has caused serious environmental damage and attracted public attention. (Haryadi et al., 2022) Likewise, deforestation and land clearing on the island of Kalimantan due to the expansion of coal mines are part of a broader picture in which the mining industry still often operates with significant environmental risks.(Bridge & McManus, 2000)

The above condition raises fundamental questions: how can Indonesia's environmental criminal evidence system adapt to the technical and geographical challenges posed by mining-related damage, and how can geospatial technology be used as a primary instrument for building credible criminal evidence? These questions then demand a study that combines criminal-law approaches, geospatial technology, and environmental forensics to develop an effective proof model. The absence or weakness of this technological integration not only hinders law enforcement but also undermines the deterrent effect and appreciation for environmental justice and the rights of future generations to live in a healthy environment. In this regard, this research arises from the need to strengthen the normative and operational framework for environmental criminal evidence to address the unique characteristics of mining damage: large-scale, complex geography, and reliance on spatial and temporal data. Thus, the integration of environmental criminal law and geospatial technology is not merely a technical innovation but a necessity for effective environmental protection efforts amid massive national mining investments. This research is expected to open the door to the reconstruction of an adaptive, environmentally resilient, and crime-proof model in response to technological and developmental dynamics.

Based on these dynamics, this study focuses on several key issues. The main issue is the urgency of applying geospatial technology to the environmental criminal evidence system for ecological damage caused by mining activities in Indonesia. Next, a thorough analysis is needed of the extent to which the current normative framework for environmental criminal evidence in Indonesia has accommodated the use of geospatial evidence as scientific proof in criminal law enforcement. Ultimately, this research seeks to answer how the Geo-Forensic Criminal Law model can be constructed as a more effective and adaptive approach to criminal evidence for addressing environmental crimes, particularly in the mining sector.

METHOD

This research method employs a normative legal approach that analyses legislation, legal doctrines, and law enforcement practices relevant to the prosecution of environmental crimes in the mining sector.(Fernando, Dahwal, et al., 2025) The approaches used include the statute approach to examine the positive legal norms governing environmental criminal evidence instruments, such as Law Number 32 of 2009 on Environmental Protection and Management, the evidentiary provisions in the 2023 Criminal Code, and derivative regulations related to the use of environmental surveillance technology; the conceptual approach to construct the concept of geo-forensic criminal law by referring to the theory of environmental criminal liability and the scientific principles of digital-spatial evidence; and the comparative approach by comparing the practice of using geospatial evidence in environmental criminal law enforcement in other jurisdictions that have adopted similar technology in their evidentiary systems. The nature of this research is descriptive-prescriptive.(Salim et al., 2022) Descriptive in depicting the empirical and juridical conditions regarding the obstacles to proving environmental damage due to mining, and prescriptive in formulating an ideal proof model to be adopted in the Indonesian criminal justice system. The analysis technique used is content analysis, which involves processing and interpreting primary, secondary, and supporting legal materials through issue classification, normative meaning extraction, and argument synthesis oriented toward the development of legal concepts and solutions.(Fernando, Widyawati, et al., 2025) All findings were systematically analysed to produce an argument structure consistent with the problem formulation and research objectives.

RESULT AND DISCUSSIONS

1. The Urgency of Utilising Geospatial Technology as an Instrument for Environmental Criminal Evidence in the Mining Sector

Amid the dynamics of national development that prioritise investment in natural resources as a pillar of economic growth, the mining sector has emerged as one of the main subsystems contributing to state revenue, job creation, and the acceleration of industrialisation. However, empirical evidence shows that mining activities, whether for minerals, metals, coal, or new commodities like nickel and lithium, often have significant environmental impacts that are large,

complex, spatially and temporally dispersed, and occur in geographical zones that are difficult to reach and monitor directly. As a consequence, the existing environmental criminal law enforcement mechanisms struggle to provide adequate evidence to prove elements of environmental damage, cause-and-effect relationships, and the identification of responsible individuals or corporations. There is an urgent need to develop new evidentiary instruments that address the unique characteristics of mining-related environmental damage; geospatial technology is a strategic element in criminal evidence.

Mining, as an extractive activity, has specific characteristics of damage: first, the damage often occurs diffusely over large areas, sometimes crossing administrative boundaries, and changes dynamically over time; second, evidence of damage and illegal activities (such as unlicensed mining, land conversion, tailing pollution, land use change) is often found in remote places, dense forests, or wetlands that are difficult for field inspectors to reach; third, perpetrators often operate complex production chains, including subcontractors, shell corporations, and foreign investors, making it difficult to trace the direct identity of the perpetrators; fourth, the environmental damage that occurs requires scientific measurement to display the causal relationship between mining activities and ecological damage, including land cover change, greenhouse gas emissions, river sedimentation, habitat destruction, and water and air pollution. This specificity makes proving environmental crimes in the mining sector a challenge that far exceeds the scope of conventional proof, which relies only on field inspections, permit documents, or confessions from the perpetrators.

From the perspective of environmental criminal law, norms such as Law Number 32 of 2009 on Environmental Protection and Management (Environmental Law) establish elements of environmental crimes, including environmental damage, environmental pollution, and loss of ecological function. However, the normative implementation of this in enforcement practice is still hindered by evidentiary limitations, as criminal norms require evidence that is admissible in court, relevant, and credible. This is where the normative-operational gap becomes clear: the document-based and physical inspection evidence system does not adequately capture the spatial and temporal dynamics and characteristics of mining environmental damage. For example, when a mine opens an access road through the forest, damages land cover, and dumps tailings into a river that crosses county lines, field inspectors' ability to document the entire sequence of events under real world conditions is limited. Geospatial technology offers opportunities such as high resolution

satellite imagery, drone monitoring, LiDAR, geographic information systems (GIS), and temporal land cover change mapping, which can capture traces that were previously "invisible" to conventional inspections.

Contemporary criminological theories provide strong conceptual legitimacy to the urgency of utilising geospatial technology in environmental law enforcement. Environmental Criminology emphasises that the physical environment not only serves as the backdrop for criminal acts but also plays a determining role in facilitating, triggering, or covering up the traces of environmental crimes. (Wortley & Mazerolle, 2008) Environmental crimes such as illegal mining, illegal logging, and ecosystem destruction are essentially crimes that manifest in space and are discernible through changes in the landscape. In line with that, the approach of the Geography of Crime (crime geography) examines the causal relationship between criminal phenomena and spatial configurations such as accessibility, remoteness, topography, and infrastructure networks, which often drive the illegal exploitation of natural resources. In this study, the use of Geographic Information System (GIS) is not merely a technical tool but an epistemological framework that enables the mapping of crime patterns through the integration of spatial, temporal, and ecological dimensions, allowing law enforcement agencies to detect hidden loci delicti, predict illegal mining expansion, and scientifically assess the risk of further damage. The concept of Forensic GIS has evolved as a paradigm that positions spatial data as digital forensic evidence that can be tested in the criminal prosecution process. Forensic GIS provides digital spatial trails with a chain of custody and metadata authentication, so that its mapping results can be audited, verified, and accounted for in court, on a par with other scientific evidence. By combining multi-temporal satellite imagery, LiDAR, UAV/drone surveillance, and topographic change modelling, this approach provides an objective reconstruction of the case, including assessing the volume of soil lost to illegal mining and mapping forest-cover changes that directly correlate with mining activities. The integration of Environmental Criminology, Geography of Crime, and Forensic GIS not only enriches investigative capabilities but also transforms the paradigm of environmental criminal law from the initially reactive-conventional to the proactive-scientific, based on evidence that can be observed, measured, and rationally retested.

From the perspective of criminal law, the chain-of-custody approach and data authentication become critical to presenting geospatial evidence that is admissible in court. The use of geospatial

technology is not merely a technical addition, but a strengthening of the integration between forensic science, spatial mapping, and environmental criminal evidence systems.

The advantages of integrating geospatial technology in environmental criminal evidence, particularly in the mining sector, can be outlined in several aspects. First, efficiency and range of evidence: satellite imagery and drone monitoring enable the recording of mining activities, land-cover changes, and environmental impacts in real time or near real time, including in areas that are difficult to access or hazardous for field personnel. Second, the spatio-temporal dimension: geospatial technology captures data with geographic coordinates, timestamps, and metadata, enabling time-series analysis of changes over time, such as before-and-after mining, or post-operation damage estimation. This is key in proving the cause-and-effect relationship between mining activities and dynamic environmental damage. Third, strong evidence visualisation: land-change maps; overlays between mining permits and land cover; and maps of mining road elements, tailings dumps, and river sedimentation can be presented in a digital format that is easy for law enforcement and courts to interpret, enhancing the persuasive power of the evidence. Fourth, multivariable data integration: in addition to visual images, geospatial data can be combined with environmental data (water quality, dust, emissions), permit data, and social data (community conflicts), thereby enhancing the contextualization of evidence and reinforcing a holistic narrative of damage. Fifth, accuracy and objectivity: geospatial technology reduces reliance on confessions from perpetrators or testimonies that can be manipulated, as it provides digital recordings that can be independently verified.

As part of strengthening oversight and proving environmental violations and illegal mining, KLHK has developed and implemented several official instruments based on geospatial technology. For example, monitoring systems such as SIMPEL (Environmental Emission Monitoring Information System) are used to monitor emissions from the industrial and mining sectors in real time. In addition, the KLHK collaborates with BIG and related agencies, using satellite imagery and uncrewed aerial vehicles (UAVs/drones) for monitoring and law enforcement operations.(*BIG Dan KLHK Bekerjasama Dalam Penyusunan Peta Rawan Kebakaran Hutan dan Lahan*, n.d.)

As an implementation figure, on July 2-3, 2025, the Ministry of Environment and Forestry, thru the Directorate General of Law Enforcement of Forestry (Ditjen Gakkum), along with a joint team consisting of the DAS Rescue Task Force, the Directorate General of Forestry Planning, the

TNI Military Police, the PPNS Supervisory Team, the Brimob, and the Bogor Regency Public Works and Public Housing Office, successfully enforced the cessation of illegal limestone mining activities in the limited production forest area of Gunung Karang, Klapanunggal District, Bogor Regency, West Java. The illegal mining activities are located at four points in the upper reaches of the Bekasi watershed and have caused environmental damage of around 50 hectares, with excavation depths reaching 10–20 meters, significantly altering the area's contours. In the operation, the authorities secured 9 excavators, 3 dump trucks, and 9 workers who were at the location for further investigation. The government emphasised that the act constitutes a violation of Article 78 Paragraph (2) in conjunction with Article 50 Paragraph (3) letter a of the Republic of Indonesia Law No. 41 of 1999 concerning Forestry as amended by Law No. 6 of 2023 (Job Creation Law), with a maximum prison sentence of 10 years and a fine of up to Rp7.5 billion. This enforcement is presented as a swift step to prevent broader ecological damage and to demonstrate the government's commitment to combating illegal mining. This crime threatens environmental sustainability and the management of national forest areas. (*Tim Gabungan Tertibkan Tambang Ilegal - NOA.Co.Id*, n.d.) The institutionalisation of these geospatial instruments is not merely theoretical. Still, it has entered the realm of operational monitoring and evidence, reinforcing the argument that geospatial evidence must be normatively accommodated within the framework of environmental criminal law.

However, it must be acknowledged that the application of geospatial technology in environmental criminal evidence also faces substantive obstacles. From a normative perspective, the regulation of digital-spatial evidence in Indonesia has not yet fully kept pace with technological developments; for example, there are no explicit provisions governing the use of satellite imagery or drone data as primary evidence in environmental trials. From an institutional perspective, law enforcement and environmental regulators sometimes lack the technical competence to process, verify, and interpret geospatial data for forensic purposes. From an operational perspective, challenges such as the authentication of digital evidence (digital chain of custody), the validity of metadata, interoperability between systems, and the admissibility of evidence in court must be addressed. Spatial challenges also arise when the mine's development area spans administrative zones or state borders, necessitating the compilation of cross-border data. Moreover, natural conditions such as cloud cover, rainy seasons, and dense vegetation can affect the quality of satellite or drone imagery and complicate interpretation.

In the mining sector, the urgency of geospatial technology becomes increasingly apparent when linked to trends in the extractive industry, such as electric batteries, rare earth metals, and national strategic projects (PSN) within the framework of a green economy. For example, in the development of nickel-cobalt batteries in Sulawesi and Kalimantan, land-cover changes, deforestation, and dispersed tailings not only cause ecological damage but also pose environmental criminal risks that are difficult to trace through traditional methods. When access roads are built through forested areas, large amounts of soil are displaced, and mining waste is dumped into riverbeds; these events require continuous, clear spatial recordings to serve as evidence in criminal cases. Geospatial technology, through pre- and post-mining analysis, land-cover comparison, river sedimentation change monitoring, and nighttime activity detection (thermal imaging), opens opportunities to present previously unattainable evidence.

From the perspective of environmental criminal law deterrence, strengthening evidence through geospatial technology signals to corporate actors and investors that extractive activities with high ecological risks cannot hide behind the sluggishness of conventional oversight. With the availability of spatial-verification data and change mapping, law enforcement can respond more quickly, initiate asset detention or seizure actions, and bring digital evidence into the litigation process. This model reinforces the principle of modern criminal law that environmental crimes may be subject not only to administrative or civil sanctions but also to criminal penalties, provided that the evidence is forensically substantiated. The integration of geospatial technology into the environmental criminal evidence system is not only technical but also strategic for strengthening sustainable investment governance and enforcing ecological justice.

The Risk Society theory by Ulrich Beck emphasises that modern society faces human-made risks that are global, widespread, and unlimited, thereby requiring new control mechanisms.(Sørensen, 2018) In the context of mining, environmental damage is not merely an individual consequence but the result of a large-scale extractive investment system that demands monitoring and proof based on spatial data (geo-risk); thus, criminal prosecution must also evolve from an actor-centred paradigm to a risk-centred paradigm. This theory supports the argument that environmental criminal prosecution must utilise technology capable of entering the spatiotemporal dimension and measuring large-scale, dispersed damage that can only be addressed through geo-forensics. Furthermore, the Technology Governance Theory emphasises that modern governance must integrate technology, data, and regulation to control the externalities of large investments. In

this context, environmental criminal prosecution through geospatial technology is a concrete manifestation of technology governance aimed at overseeing extractive investments.

From the perspective of criminal-law evidence, the application of geospatial technology in the mining sector should be viewed as an evolution of norms and practices, not merely a technical modernisation. This is because the presentation of evidence in court must meet the requirements of being lawful, relevant, and verifiable. Geospatial data with complete metadata (coordinates, timestamp, sensor, source) enables the presentation of evidence with a chain of custody, traceability, and scientific validity, which have been the main obstacles to proving environmental crimes. The urgency of using geospatial technology as an instrument for prosecuting environmental crimes in mining is very high: it fills a methodological gap, strengthens the legitimacy of enforcement, and affirms that the governance of large investments must not be detached from environmental criminal responsibility.

2. Analysis of the Normative Framework of the Environmental Criminal Evidence System in Indonesia Regarding the Use of Geospatial Evidence

The evidentiary system in environmental criminal enforcement in Indonesia holds a strategic position because the characteristics of crimes in this sector are often latent, dispersed, and difficult to observe directly through traditional evidentiary methods. Law No. 32 of 2009 has specifically regulated the mechanisms for investigation and proof as a lex specialis to address that complexity. In Article 95 paragraph (1), this law emphasises the implementation of integrated law enforcement involving PPNS, the Police, and the Prosecutor's Office, coordinated by the Minister, to strengthen the institutional framework for environmental criminal investigations. This indicates that proving environmental crimes cannot be separated from a collaborative approach and technological support in evidence collection, including geospatial evidence.

Article 96 of the PPLH Law explicitly regulates the admissible evidence in environmental criminal prosecutions, including general evidence as stipulated in criminal procedural law: witness testimony, expert testimony, documents, indications, the defendant's statements, and other evidence regulated by legislation. This provision expands the objects of proof beyond the classical formulation in the Criminal Procedure Code (KUHAP), thereby allowing the development of scientific proof methods such as geospatial modelling, satellite imagery, or drone monitoring recordings. The explanation of Article 96 letter f even emphasises that other evidence includes

electronic information and visual recordings, as well as maps and images that can be read and understood. This normative authorisation serves as the legal basis for the inclusion of geo-forensic evidence in environmental criminal prosecution.

Strengthening the normative framework for environmental criminal evidence utilising geospatial data must take into account the position of other types of evidence as regulated under Article 184 of the Criminal Procedure Code. Satellite imagery, GIS mapping, and drone recordings can be classified as documentary or indicative evidence, depending on the form of presentation and the involvement of experts in their interpretation. This position is reinforced by the ITE Law No. 11/2008 jo. Law No. 19/2016, which recognises electronic information and/or electronic documents as valid legal evidence, so digital-spatial evidence is no longer viewed as secondary evidence requiring additional verification. Perma No. 4 of 2020 regarding the administration and trial of criminal cases electronically also emphasises that digital evidence can be submitted and assessed based on authentication parameters, metadata integrity, and chain of custody.

In the context of investigations, the Environmental Protection and Management Law (UU PPLH) also provides special authority for Environmental Supervisory Officers (PPNS) to conduct photography, audio-visual recording, and enter locations where criminal acts are committed, as regulated in Article 94 paragraph (2) letter i. This authority is highly relevant for collecting spatial data in mining areas, such as using drones to photograph open areas damaged by open-pit mining or river sedimentation caused by illegal gold mining. Thus, the legal framework has accommodated technology-based evidence collection methods and direct field observations.
However, this norm has not yet been supported by adequate technical standardisation, in the form of derivative regulations governing the validity and authentication of geospatial data as evidence. This is evident from the absence of regulations that explain chain-of-custody procedures for mapping data, including the necessary metadata to ensure its authenticity and immutability. Although the Environmental Protection and Management Law (UU PPLH) provides a basis for the recognition of electronic evidence, the absence of procedural safeguards for spatial data has the potential to cause debates in court, such as regarding the accuracy of satellite resolution, changes in observation time, or the integrity of digital documents that are susceptible to manipulation.

In this regard, expert testimony becomes central in environmental criminal prosecutions, given that geospatial evidence serves not only as a recording tool but also as a scientific

representation of the extent of ecological damage. Article 96 letter b explicitly mentions expert testimony as the primary evidence. In the context of mining, geospatial, geological, and ecological experts can provide interpretative explanations regarding the cause-and-effect relationship between mining activities and environmental damage, as demonstrated through temporal mapping and multi-layer analysis. Visual evidence, such as satellite images before and after mining activities, can corroborate the element of criminality.

Although the legal basis for environmental criminal evidence appears strong, there are weaknesses in the synchronisation of the evidentiary system between regulations. The Environmental Protection and Management Law (UU PPLH) is adequate in regulating the subject matter of investigations. However, the general rules of evidence still adhere to the Criminal Procedure Code (KUHAP) as the applicable criminal procedural law. The KUHAP itself does not explicitly mention geospatial evidence, so the evidentiary forum requires an argument regarding its status as either documentary or circumstantial evidence, depending on how the data is presented. In practice, judges tend to classify satellite images as documents if they are in photographic form and as evidence if expert interpretation is required to link the data to the criminal act. This choice of categorisation has consequences for the evidentiary value, which can weaken if the interpretation is not consistently applied at every level of the judiciary.

Furthermore, the regulation of integrated law enforcement in Article 95 paragraph (1) needs to be supported by cross-agency data interoperability, especially when handling illegal mining, which often involves expanding mining areas across administrative boundaries. Without integrating geospatial databases, investigators face difficulties precisely mapping the locus delicti for prosecution purposes. The uncertainty of territorial boundaries is one of the biggest obstacles in determining the elements of unlawfulness in environmental crimes.

The recognition of Article 96 letter f regarding maps and images as evidence opens the possibility of using evidence automation, such as real-time monitoring of deforestation in mining areas through multi-spectral image analysis, but the provision remains too general. This instrument has not yet been made a normative element that requires mining industry actors to submit spatial data to law enforcement as part of their environmental reporting obligations. As a result, criminal prosecutions still often rely on data collected by investigators rather than official information from the corporate perpetrators of the crime.

From the perspective of criminal liability, Articles 97–98 of the Environmental Protection and Management Law (UU PPLH) state that environmental crimes are offences that can incur severe penalties, especially when environmental damage exceeds quality standards or harms human victims. The application of this sanction requires strong, irrefutable evidence, making geospatial proof especially urgent to meet the evidentiary threshold for a judge's conviction. Thus, the refinement of procedural aspects of evidence presentation is a normative necessity to ensure that geospatial evidence does not weaken in the face of the beyond-reasonable-doubt standard.

3. Geo-Forensic Criminal Law Model as an Innovation in Criminal Evidence for the Effectiveness of Environmental Law Enforcement

The integration of geospatial technology into environmental criminal prosecution demands a reconstruction of the criminal law concept that is more adaptive to technological developments, especially in the mining sector, which plays a significant role in the national economy yet poses a risk of extensive ecological damage. The Geo-Forensic Criminal Law model is intended as an approach that uses spatio-temporal data as the primary basis for reconstructing environmental crimes, especially when the damage occurs in a hidden, fragmented manner and is difficult to observe through conventional field inspections. This approach is a modern articulation of the idea of crime mapping and spatial causality in Environmental Criminology, where space is not merely a container of events, but an active element that reveals crime patterns and empirical traces that cannot be scientifically disputed.

Within the framework of Indonesian law, the formulation of this model is urgently needed, given that environmental crimes, particularly in the mining sector, often involve systematic and corporate forms of violation. Mining activities without permits or exceeding permit limits, massive deforestation for mining infrastructure development, dumping of tailings into riverbeds, and the expansion of mineral export terminals are often unmonitored due to limited oversight capacity, difficult geographical terrain, and weak evidence documentation during incidents. Geo-forensic evidence leverages digital traces such as high-resolution satellite imagery, GIS-based mapping, LiDAR, and drone monitoring to establish cause-and-effect relationships between human actions and environmental damage across spatial and temporal dimensions, thereby linking the perpetrators to the ecological consequences.

The geo-forensic-based proof model developed in Indonesia needs to refer to international best practices to strengthen normative legitimacy and scientific proof capacity in environmental criminal cases. In the United States, the Environmental Protection Agency (EPA) operates the Environmental Crime Mapping System. This integrative platform combines environmental monitoring data, permitting information, field investigation results, and satellite imagery data into a unified investigative system.(Thomson & Samuels-Jones, 2022) The use of forensic GIS by the EPA in handling the Kalamazoo River Oil Spill case and mining crimes in the Appalachian region serves as strong evidence that geospatial technology can play a key role as primary evidence in proving causal elements, such as increased sedimentation levels due to mining activities or waterway contamination traced based on surface flow patterns. This system is reinforced through its connections to NASA's remote sensing and the United States Geological Survey (USGS) database, which provide elevation models, rock types, soil textures, and surface movement data to analyse the extent of ecological crime impacts with precision and over time. This practice demonstrates an interactive, multi-temporal, and real-time criminal evidence model, where spatial changes are directly related to human activities, allowing for the affirmation of intent, the nature of the perpetrator's involvement, and the ecological impacts that occur. An approach like this can provide important insights for developing criminal mining evidence in Indonesia, particularly for coal in Kalimantan and nickel in Sulawesi, which have geo-ecological characteristics similar to those of extractive regions in the United States.

In the European Union, the prosecution of environmental crimes is undergoing increasingly progressive developments through the implementation of the EU Environmental Crime Directive, which strengthens the legitimacy of cross-sectoral and cross-border law enforcement.(Faure, 2024) One of its instrument innovations is the integration of the Copernicus Earth Observation System into the investigation and litigation processes of environmental crimes. Member countries such as Germany, the Netherlands, and France have recognised remote sensing evidence as a legitimate scientific tool, especially for enforcing cross-border measures against illegal mining, industrial pollution, and environmental permit violations. The Sentinel satellite system, which is the backbone of Copernicus, provides multi-spectral data that enable advanced spatial analysis, ranging from heatmaps of vegetation changes and sediment and mudflow mapping to turbidity detection in river bodies, to assess the temporal and objective impacts of extractive activities. This visualisation is used not only as proof but also as evidentiary material to directly show the actus

reus in the form of illegal environmental changes, as well as to support inferences regarding the perpetrator's involvement and the extent of ecological damage. This practice demonstrates that the modern criminal justice system in Europe has positioned geo-forensic evidence as a crucial component in proving elements of a crime, with sufficient authentication through expert verification and the reliability of satellite data, which is a product of scientifically authorised technology.

Australia is a jurisdiction that progressively places geospatial data as the basis for monitoring and criminal prosecution in the mining sector. In the mining legal regimes of states such as Queensland and Western Australia, corporate spatial reporting is mandatory as part of the requirements for mining operation permit approval. Through legal instruments such as the Queensland Environmental Protection Act and the Mining Rehabilitation Fund Act, and regulations in Western Australia, mining companies are required to submit Operational Geospatial Mine Data, which includes mine boundaries, stockpile locations, topographical changes, and land reclamation data, periodically through the local government's digital reporting system. Non-compliance with the submission of this spatial data is initially classified as an administrative violation and may escalate to a criminal offence if there are indications of information concealment, environmental destruction, or violations of land rehabilitation obligations. In that framework, geospatial data becomes an inherent part of the compliance monitoring system, not just evidence sought after a violation has occurred. The government can automatically conduct spatial audits using Sentinel satellite imagery, UAVs, and DEM modelling to detect land-use changes that do not comply with permits. This approach places the state in a proactive and precise position in law enforcement, as evidence of mining crimes is created and recorded as operations proceed, rather than relying on external reports or incidental findings.

Learning from these three jurisdictions, the design of the Geo-Forensic Criminal Law Model in Indonesia must have four main pillars: (1) Geospatial Legality Recognition or explicit recognition of geo-forensic evidence as a valid scientific proof in criminal law; (2) Geospatial Data Governance in the form of corporate and state obligations in reporting and storing spatial data; (3) Operational Investigative Mechanism thru coordination of law enforcement with national mapping agencies such as BIG, BRIN, and KLHK; and (4) Judicial Admissibility Standard that ensures the acceptance of spatial evidence in court meets the technical and procedural standards of scientific proof.

In the technical context of evidence, the geo-forensic model requires the integration of the spatial chain of custody as a mandatory element. Spatial evidence generated by satellites, drones, or GIS must be recorded with complete metadata, such as the time of capture (timestamp), geographic coordinates, sensor name, and data transmission path. This principle protects evidence from legal challenges regarding data authenticity, such as undocumented digital manipulation or editing. This standard is similar to the Forensic Digital Evidence Protocol applied in criminal justice in the United States and Australia. In Indonesia, there are no detailed provisions regarding the authentication of digital-spatial evidence in the Criminal Procedure Code (KUHAP) or the Environmental Protection and Management Law (UU PPLH). As a result, the evidence may be rejected if the defence questions the data's integrity. The geo-forensic model fills this gap by proposing specific procedural standards for forensic-level mapping content.

This model also strengthens the position of expert testimony in environmental criminal prosecution. If geospatial data is the technical language that "reads the traces of ecosystem damage," then the expert functions as a visual translator into the structure of legal argumentation. Geospatial experts ensure that satellite imagery is not just a visualisation of inanimate objects, but a scientific narrative that asserts that an action causes ecological impacts at a specific point in time, thereby objectively proving the elements of criminal causality. In many mining cases, such as the destruction of watersheds, changes in the topography of mining areas, or the intensity of passive sedimentation, the involvement of experts becomes crucial in bridging the gap between digital facts and the proof of criminal elements.

In addition, this model enables corporate criminal liability based on Spatial Accountability Mapping. In the structure of large companies, ownership and control of mining operations are often obscured by subcontracting or special-purpose vehicles to conceal the main actors. When geo-forensic mapping is conducted with an overlay of permits and shareholder structures, the discovery of corporate control becomes easier. It can clarify the relationship between the perpetrators and their ecological impact. Thus, this model aligns with the increasingly developed doctrine of piercing the corporate veil in international environmental crimes, where law enforcement penetrates the complex corporate structure to identify the individuals criminally responsible.

The normative foundation of the Geo-Forensic Criminal Law Model is built on the legal recognition of scientific evidence in the Indonesian criminal justice system, particularly electronic

evidence and visual recordings as regulated in Article 96 letter f of the Environmental Protection and Management Law (UU PPLH) and the general provisions of evidence in the Criminal Procedure Code (KUHAP). This strengthening of the foundation demands a more explicit formulation that geospatial data, including satellite imagery, UAV data, and GIS-based maps, constitute valid evidence that can stand alone and are not always treated as supplementary evidence. With this foundation, geospatial technology is no longer considered merely an investigative instrument, but rather an integral part of the scientific reconstruction of environmental crimes.

4. Geospatial Investigation Flow

This model develops a spatiotemporal investigative workflow that records events before, during, and after the crime. The process includes: (a) identification of land cover changes using satellite imagery; (b) field verification through UAV/drone and geospatial sensors; (c) mapping the causal relationship between mining activities and damage traces; and (d) digital documentation through a spatial chain of custody with complete metadata. With this process, the proof no longer relies on transient physical findings, but on a serial record of objective data that can be scientifically retested.

5. The Role of Experts in the Interpretation of Geo-Evidence

In this system, expert testimony holds a central position as the translator of geospatial evidence into the structure of legal argumentation. Geospatial, geological, and ecological experts explain the scientific meaning of recorded spatial changes, such as watershed damage, sedimentation, or illegal expansion of mining areas, to prove elements of criminal causality. Thus, experts are not merely supporting witnesses but epistemic actors who bridge digital facts and elements of the crime, enabling judges to gain confidence in their decisions based on empirical, measurable evidence.

6. Corporate Criminal Liability Based on Spatial Accountability Mapping

This model strengthens corporate criminal liability through the Spatial Accountability Mapping approach, which overlays evidence of damage with business license areas, contractor chains, and company ownership structures. With this mapping, corporate perpetrators can no

longer hide behind subcontractor contracts or legal entity separations because the damage traces are directly documented on the business entities that control the operations. This approach aligns with the doctrine of piercing the corporate veil in environmental crimes and narrows the space for corporate impunity.

7. Judicial Standards in the Acceptance of Geospatial Evidence (Admissibility Rules)

Strengthening this model requires establishing judicial acceptance standards that ensure geospatial evidence meets the criteria of scientific verifiability, chain-of-custody integrity, authenticity, and reliability. These standards must be outlined through judicial technical guidelines or specific regulations so that judges have clear assessment instruments for the quality of geospatial evidence. Thus, the admissibility of spatial evidence does not depend on the judge's subjective preferences but on scientific parameters that can be objectively tested in court.

8. Strengthening Geo-Forensic Enforcement Institutions

To make this model operational, a specialised institution is needed: a Geo-Forensic Environmental Crime Task Force that integrates KLHK-Gakkum, BIG, BRIN, the Police, and the Prosecutor's Office into a single command system. This unit is responsible for geospatial investigations, national data management, and digital-spatial forensic training for law enforcement officers. This institutional strengthening ensures that the use of technology does not end with a pilot project but becomes a standard surveillance regime for environmental criminal prosecution in the mining sector. The geo-forensic framework also offers solutions in localising the locus delicti in environmental crimes, especially in boundary disputes. Precise coordinate measurements help avoid potential lawsuits arising from vague or unclear allegations about where the act was committed. Because many mining areas span administrative boundaries between districts and even provinces, the spatial locus delicti is important for ensuring the absolute competence of investigators, prosecutors, and courts. This model reduces legal loopholes that perpetrators often exploit to delay judicial processes through jurisdictional objections.

From the perspective of continuous monitoring, the geo-forensic model enables a paradigm shift from reactive criminal law to proactive, predictive enforcement. By using an early detection system, such as monitoring for abnormal changes in vegetation or increased waste disposal, investigators can immediately take preventive legal actions, such as halting operations, installing

surveillance lines, or confiscating equipment. This strengthens the function of criminal law as an instrument of ecological protection, not merely a tool for retribution after irreversible damage has occurred.

From an institutional perspective, implementing this model requires strengthening the authority of geospatial forensic experts within law enforcement agencies. The existence of geospatial criminal investigation units, such as the EPA Criminal Investigation Division or the EU Environmental Crime Unit, serves as an example of specialised institutions with multidisciplinary competencies in criminal law, geospatial analysis, geology, and environmental science. In Indonesia, this institution can be placed within the KLHK structure, in collaboration with BIG, BRIN, the Police, and the Prosecutor's Office, as the Geo-Forensic Environmental Crime Task Force to address limitations in inter-agency coordination.

In terms of weaknesses, this model must address challenges related to legal legitimacy and judges' trust in digital scientific evidence. Judicial awareness of geospatial technology has not developed evenly. There needs to be a judicial training program that enhances judges' and prosecutors' capacity to assess the quality of geospatial evidence, so that decisions are not biased against conventional forms of evidence. This has been implemented in the United States and the European Union through continuing legal education specifically on digital and scientific evidence.

As a pillar of transformation, the Geo-Forensic Criminal Law Model promotes the reform of evidentiary law in Indonesia with three main agendas: (1) the normative recognition of explicit spatial evidence in the criminal evidentiary law; (2) the development of technical protocols to ensure the integrity of geospatial data; and (3) multisector collaboration between environmental regulators, digital forensic experts, law enforcement agencies, and national mapping institutions. Comparisons with other jurisdictions show that countries that successfully enforce geoforensic-based environmental law not only impose sanctions but also ensure that evidentiary instruments capture ecological realities with scientific precision.

Through a systematically built system, this model encourages a shift in the paradigm of proof in environmental criminal cases from a conventional approach that tends to focus on direct evidence and testimonium de auditu, toward a regime of proof based on scientific evidence (evidence-driven), data intensive, and supported by technology (technology-supported). This shift reflects the demands of the latent, dispersed, and complex nature of environmental crimes, which can often be traced only through ecological footprints recorded by data-engineering and

monitoring technologies. This new paradigm not only strengthens the quality of evidence presented in court but also affirms the position of scientific expert testimony, laboratory analysis, satellite imagery, geospatial data, and digital footprints as high probative value instruments in uncovering elements of environmental crimes, including consequences, causal relationships, and the extent of environmental damage. Thus, the system of proof has shifted from mere factual proof to scientific proof that is measurable and empirically accountable. Moreover, technological support ensures that the proof process remains accountable and minimises the subjective bias of law enforcement, in line with the due process of law principle and the precautionary principle, which serve as the normative foundation for environmental criminal law enforcement. The model expands access to hard-to-find evidence and enables law enforcement authorities to anticipate, detect, and prove environmental crimes more effectively, including against corporate actors who possess asymmetric power to conceal facts and manipulate information. Thus, this structured model catalyses reforming environmental criminal evidence that is more compatible with the dynamics of modern ecological crimes and aligned with the direction of criminal law development based on science and technology, so that elements of environmental crimes no longer rely solely on witnesses and administrative documents, but on signs of ecosystem damage detectable by technology. Such an approach is crucial for law enforcement in the mining sector, especially in situations where the damage has already spread extensively and burdens future generations.

CONCLUSION

The utilisation of geospatial technology in environmental criminal prosecution in the mining sector is an urgent need due to the extensive, widespread, and difficult-to-detect nature of ecological damage that is often not detected by conventional methods. Technologies such as satellite imagery, GIS, LiDAR, and drones enable the spatial and temporal identification of environmental damage, allowing the elements of environmental loss, causal relationships, and connections to mining activities to be proven more objectively and accurately. Normatively, Indonesian law has created space for the use of geospatial evidence by recognising electronic information, maps, and visual documentation in environmental criminal proceedings. However, the absence of standards regarding data authentication, digital chain of custody, inter-agency interoperability, and guidelines for the acceptance of evidence in court has resulted in the suboptimal evidentiary value of geospatial evidence.

To address this condition, this research offers the concept of Geo-Forensic Criminal Law, which places spatio-temporal data as the basis for proving mining crimes. This model includes the recognition of geo-forensic evidence as scientific proof, integrated geospatial data management, inter-agency investigative collaboration, and judicial acceptance standards based on scientific validity. Through this approach, corporate criminal liability can be strengthened by spatial mapping that connects environmental damage with business permits and responsible parties. Ultimately, this model encourages a more data-driven, technology-based, and scientifically-evidenced environmental criminal justice system, thereby enhancing the effectiveness of law enforcement, achieving ecological justice, and ensuring that mining development aligns with environmental protection.

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