

Remote Sensing for Forensic Investigations: A Review of Techniques and Applications in Clandestine Grave Detection

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ABSTRACT

The location of clandestine graves is a critical challenge in forensic investigations. This review evaluates the application of remote sensing technologies to address this challenge. A comprehensive literature search was conducted across scientific databases (Web of Science, Scopus, IEEE Xplore, Google Scholar, PubMed Central, ScienceDirect), using keywords related to remote sensing, forensic science, and burial detection. Peer-reviewed articles and books focusing on remote sensing applications in forensic contexts, especially clandestine grave detection, were included. Data on methods, location, target, spectral indices, and key findings were extracted. A significant increase in publications in this field was observed, particularly since 2018. Techniques included multispectral and hyperspectral imaging (satellite and UAV), LiDAR, GPR, ERT, and thermal imaging. Spectral indices (NDVI, GNDVI, VARI) were used to analyze vegetation stress. Success varied with burial depth, soil type, vegetation cover, and time since burial. Geophysical methods provided valuable subsurface information, but effectiveness decreased over time. Remote sensing offers powerful tools for forensic investigations, enabling non-invasive assessment and improved detection of clandestine graves. A multidisciplinary approach, combining multiple remote sensing techniques with geophysical methods, is crucial. Further research is needed to optimize techniques for diverse environments, improve detection of older burials, and develop standardized methodologies.

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1. INTRODUCTION

The ability to locate and analyze concealed evidence is a cornerstone of forensic science, with applications ranging from criminal investigations and humanitarian efforts to archaeological research. Traditionally, locating buried remains or objects has relied on witness testimony, laborious manual searches, or invasive techniques like excavation. However, these methods can be time-consuming, costly, potentially destructive, and often unsuccessful, particularly when dealing with large or obscured areas, or when significant time has elapsed. In recent decades, advancements in remote sensing technologies have offered a powerful suite of non-destructive tools that can dramatically improve our ability to detect and characterize subsurface features, offering a significant advantage in diverse forensic scenarios [1]. These technologies, originally developed for fields like environmental monitoring and resource exploration, are increasingly finding application in the search for clandestine graves, buried evidence, and other hidden features of forensic interest.

The growing interest in applying remote sensing to forensic contexts stems from its potential to provide rapid, wide-area assessments, often without disturbing the site in question. Techniques like multispectral and hyperspectral imaging, LiDAR, ground-penetrating radar (GPR), and thermal imaging can detect subtle changes in vegetation, soil properties, and topography that may indicate the presence of buried remains or objects. These changes can result from disturbances to the soil, the presence of decomposition products, or alterations in water drainage patterns. By analyzing these remotely sensed signals, investigators can narrow down search areas,

This review article aims to synthesize the current state of knowledge regarding the application of remote sensing techniques to forensic investigations, with a particular focus on the detection of clandestine graves. We systematically examine the diverse range of methods employed, including aerial and satellite imagery analysis, geophysical surveys, and the use of specialized sensors. The effectiveness of different techniques, the challenges encountered, and the evolution of the field over time are critically assessed. The principal conclusion drawn from this review is that remote sensing, particularly when integrated within a multidisciplinary approach, offers a powerful and increasingly essential set of tools for modern forensic science, offering improved detection capabilities, reduced investigation times, and a more non-invasive approach to locating buried evidence. However, the review also emphasizes the importance of continued method refinement and validation across diverse environments to maximize the reliability and applicability of these powerful technologies.

This article presents a literature review that focuses on research related to the use of remote sensing technologies in forensic applications. The analysis was conducted using keywords that relates remote sensing and forensic scenarios like ("mass" OR "clandestine" OR "common" OR "unmarked") AND "grave" AND ("remote sensing" OR "UAV"), which identified a total of 37 research articles in several databases. The reviewed studies agree that remote sensing techniques, such as the use of multispectral imagery, thermal imagery, LiDAR technology, and geophysical methods, are fundamental for the discovery of clandestine graves. These non-invasive techniques reduce costs and prevent damage to the environment, representing a field that can be expanded and associated with other areas of study. Figure 1 shows a network of relationships between the keywords of the 37 articles found made with VOSViewer software [2], [3].

2.1. Literature search strategy

- Web of Science (Clarivate Analytics): A multidisciplinary database covering a wide range of scientific publications.
- Scopus (Elsevier): Another comprehensive database with broad coverage of scientific literature.

- IEEE Xplore: Focused on electrical engineering, computer science, and related fields, relevant for remote sensing technologies.
- Google Scholar: A broader search engine for scholarly literature, used to capture any publications not indexed in the more specialized databases.
- PubMed Central and ScienceDirect Search engines for publications in science, technology and medicine.

2.2. Inclusion and exclusion criteria

Articles were included in the review if they met the following criteria:

- Peer-Reviewed: Published in a peer-reviewed journal or a reputable conference proceeding. Books were included based on the publisher's reputation and the authors' expertise.
- Focus on Remote Sensing: The primary focus of the article had to be on the application of remote sensing techniques.
- Forensic Relevance: The article had to discuss the application of remote sensing to a forensic problem, or present methods with clear potential applicability to forensic investigations (e.g., archaeological studies with relevant methodologies). This included, but was not limited to, the detection of graves, buried objects, or alterations to the environment relevant to a crime scene.
- English Language: The article had to be published in English.
- Articles were excluded if they:
 - Were purely theoretical, without any experimental validation or case studies.
 - Focused solely on image processing techniques without a clear link to a forensic application.
 - Were reviews that did not provide a synthesis of original research (although reviews were used to identify primary sources).
 - Were inaccessible (e.g., not available through the databases or interlibrary loan).

The selection and review of studies adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure methodological rigor and reproducibility. The initial search across the identified databases yielded a total of 37 potentially relevant records after removing duplicates. These articles underwent a screening process based on title and abstract relevance, followed by a full-text assessment against the inclusion criteria established in Section 2.2. Ultimately, all 37 selected studies met the quality standards for qualitative synthesis, focusing on the application of remote sensing technologies in forensic contexts.

3. RESULTS

The oldest article identified in the search, published in 2002 [4], focused on evaluating remote sensing methods and the hazard potential associated with glacial lakes in the Swiss Alps region. The main objective was to determine the capability of remote sensing technologies to detect such lakes. Although this work used satellite image analysis, it does not have a direct relationship with forensic science.

The next article, published in 2006 by M. Kalacska and L.S. Bell [5], focuses on the detection of mass graves using remote sensing. The study presents two cases in Guatemala. The first compares in situ spectral measurements, obtained with a spectrometer, with hyperspectral imagery. The second analyzes multispectral satellite imagery to detect mass graves.

In 2007, two articles and one book related to the search equation were identified. The book explores the fundamental role of remote sensing in modern archaeology, showing how technologies such as ground-penetrating radar (GPR), magnetometry, and satellite imagery analysis enable archaeologists to discover and map hidden sites, analyze ancient landscapes, and better understand the interaction of past societies with their environment [6]. A second work, by several authors, used radar imagery and other remote sensing techniques to detect infrastructure networks and settlements [7]. While neither the book nor this publication is directly applied to forensic science, their methods for identifying objects and locations have potential applicability in this field. Finally, a third article [8] highlights the use of GPR in archaeology, mentioning advances in image processing software and its integration with GPS navigation methods, which make it an accurate and efficient tool for subsurface exploration. The study demonstrates the versatility of GPR in diverse archaeological contexts, solidifying its position as a key technology, also applicable to forensic investigation.

In 2009, the first publication on the use of remote sensing applied directly to forensic science is found [9]. The study describes the creation of two identical graves: one with livestock remains and another, a control, filled with soil. The objective was to analyze and compare the in situ spectral reflectance of both graves over a 16-month period to determine their spectral separability and detectability.

In 2012, two relevant publications were identified. The first [10] focuses on the identification of buried archaeological remains through crop marks in agricultural fields in Central Europe. It analyzes how these marks, which are visible changes in crop growth, can indicate the presence of buried structures, such as graves,

trenches, and waste pits. The study highlights that the presence of these remains can affect soil properties, particularly nutrient availability; for example, graves can increase levels of phosphorus (P) and nitrogen (N), influencing crop growth. Although forensic applications are not discussed in depth, the principles of identifying buried features through changes in vegetation could be useful for locating clandestine graves. The second publication [11] analyzes the growing application of geoscientific methods in various forensic investigations, including criminal, environmental, and humanitarian cases. The importance of these methods as a complement to traditional search techniques for locating buried objects, such as clandestine graves, weapons, and hazardous waste, is highlighted. The rapid evolution of forensic geoscience, driven by a growing number of experimental and theoretical investigations that increase the effectiveness of search operations, is emphasized. The work also outlines a general workflow for forensic searches, from remote sensing and desk studies to site reconnaissance and intrusive investigations, laying the groundwork for a detailed exploration of specific geoscientific techniques and their applications in forensic science.

In 2014, two research articles related to the search equation were published. Only one focuses on forensic science; the other [12] presents arguments for the presence of valuable metals on the Moon, supported by empirical data and theoretical models, and proposes improving lunar exploration using remote sensing techniques. The article relevant to forensic science [13] explores the potential of airborne hyperspectral imaging (HSI) to detect individual graves. Although previous studies have demonstrated the location of clandestine mass graves using HSI, detecting individual graves presents a greater challenge due to their smaller size. The results indicate that hyperspectral imaging is promising for the detection of buried remains. However, further research is needed before its practical application, including improved geolocation techniques and testing in diverse environments to improve reliability.

In 2015, Blau and Sterenberg published an article [14] that highlights the fundamental role of archaeologists and anthropologists in the recovery of buried evidence, especially human remains. The work presents an overview of the tools and knowledge necessary for the recovery and identification of skeletal remains, emphasizing the importance of a multidisciplinary approach.

In 2017, two research articles and a book were published. The book [15] focuses on forensic geophysics, a branch of geophysics applied to criminal investigation. It uses non-destructive techniques, such as ground-penetrating radar (GPR), magnetometry, and electrical resistivity, to detect buried objects (human remains or physical evidence) without damaging the site. These techniques, based on differences in the physical properties of soil and objects, create subsurface images that reveal anomalies; however, data interpretation requires expertise, as various factors can affect the signals. Forensic geophysics is a valuable tool, but its success depends on careful planning, the selection of appropriate methods, and its combination with other techniques. Another work [16] explores the potential of hyperspectral measurements to detect buried human remains, a complex task in archaeology and criminology. By capturing the detailed spectral information of soil materials, this technique seeks to identify alterations that indicate the presence of remains. The authors anticipate that this methodology could revolutionize investigations by allowing more precise and less invasive localization, saving time and resources, and preserving the integrity of the sites; however, they acknowledge the need for further research to optimize these techniques and validate their effectiveness in various contexts. Finally, a study [17] analyzes mass graves in Muthanna province, Iraq, as part of the forensic investigations by the U.S. Regime Crime Liaison Office (RCLO) to document the genocide by Saddam Hussein's regime against the Kurdish minority. The objective was to reconstruct the landscape of genocide, understand the processes that led to these mass burials, and provide scientific evidence for war crimes trials. Through an interdisciplinary approach combining geoarchaeology and forensic science, along with the use of remote sensing techniques, the researchers were able to determine the factors that influenced the selection of burial sites.

In 2018, four research articles were published. The first, conducted at the Australian Facility for Taphonomic Experimental Research, examines the techniques used to dispose of homicide victims, with a focus on mass graves (sites with two or more associated bodies). The difficulties in identifying these sites due to elapsed time and environmental obfuscation are highlighted, emphasizing the importance of forensic investigations and the fusion of methodologies such as geographic information systems (GIS), satellite imagery, unmanned aerial vehicles, and geophysical techniques, as a multidisciplinary strategy to improve results [18]. A second work explores the use of unmanned aerial vehicles (UAVs) to detect and document clandestine graves and recent human remains. It is argued that remote sensing, through the combination of sensors and advanced algorithms, offers a promising approach, although the technical and ethical challenges are acknowledged [19]. A third study investigates the potential of terrestrial LiDAR technology to detect unmarked graves. By accurately measuring changes in the ground surface over time using laser scanners, the researchers found that human graves cause detectable alterations, suggesting that LiDAR could be a fundamental tool in the search for human remains, especially in cases without visible markers [20]. Finally, the potential of aerial drone photography to detect clandestine graves is explored. Despite the advantages of this technique, its use has been limited by costs. However, technological advances have enabled the

development of affordable drones, opening up new possibilities for forensic science. The study focuses on near-infrared (NIR) photography taken from drones, which reveals features invisible to the human eye that are indicative of clandestine burials. The authors conclude that drones with NIR cameras are a promising, economical, and accessible tool for this task [21].

In 2019, an article [22] was published on the identification of covert burials, which are often shallow and visually perceptible due to disturbances in soil and vegetation. The research, conducted in Chester (England), simulated burials to evaluate the use of unmanned aerial vehicles with conventional cameras as an economical alternative to traditional methods, seeking to improve efficiency in identifying potential burial sites. However, the remote sensing techniques in this study are limited to video and image analysis in the visible spectrum.

In 2021, four articles were published. The first addresses archaeological looting in Peru, emphasizing the loss of cultural context and the need for monitoring technologies. The importance of Earth observation for identifying vulnerable sites and detecting looting activities, especially in remote areas, is highlighted [23]. Although the document relates change detection to remote sensing through spectral indices applied to satellite imagery, it does not focus directly on forensic science. A second work explores the current role of forensic archaeology and anthropology (FAA) in Sweden, identifying the need for a stronger national infrastructure and greater interdisciplinary collaboration. The results reveal a lack of standardization in procedures and variations in researcher competence, underscoring the importance of continuing education programs and clear protocols to ensure the quality of investigations involving human remains [24]. This work focuses more on the organizational structure of the FAA. A third study addresses the need for technological tools to locate clandestine graves in Mexico, a critical problem due to the high rate of forced disappearances. Through an experimental study, the potential of various remote sensing techniques, such as spectral index analysis and thermography, is explored to detect simulated burials. The results show that certain spectral indices related to vegetation nitrogen content can be indicators of the presence of buried human remains; however, the effectiveness of these techniques may vary depending on terrain conditions and grave size [25]. Finally, a fourth article is oriented towards the use of ground-penetrating radar (GPR) in the search for unlocated Indigenous graves in northern Alberta (Canada), integrating Indigenous knowledge into the research to respect local traditions. In this way, not only are ancestral remains located, but the relationship between archaeologists and communities is also strengthened, contributing to reconciliation and decolonization. The results underscore the need to incorporate Indigenous perspectives to ensure culturally sensitive and respectful archaeological projects [26].

In 2022, six investigations were published. The first [27] investigated the influence of geological and geographical determinants on the selection of clandestine grave sites, emphasizing the importance of excavation and concealment characteristics. A second study [28] delves into remote sensing techniques, using spectral indices such as NDVI and VARI to detect clandestine burials and assess vegetation stress associated with decomposing remains. This work highlights advances in unmanned aerial vehicle (UAV) and ground-penetrating radar (GPR) technologies, which improve grave identification and tracking of the movement of decomposition fluids. A third investigation [29] focuses on three natural burial grounds in the United Kingdom, examining individual graves with multispectral data accumulated over several years to overcome the limitations of previous studies. Similar to previous works, the improvement in drone technology is emphasized, facilitating the acquisition of higher resolution images to identify discrete burials. The fourth study [30] documents and protects the Brier Hill cemetery, the final resting place for impoverished people in the 19th century, which, unlike others, has been largely preserved. The research, *conducted using remote sensing methods*, reveals a complex history, where social relationships and community connections influenced the organization of burials, challenging traditional notions about paupers' cemeteries. A fifth work, more of a report than a research article, [31] located and analyzed Jewish mass graves by combining the analysis of historical aerial photographs with modern topographic techniques. By comparing images from 1944 and 2015, the grave was identified and characterized, despite terrain transformations; evidence of ground subsidence confirms its location. Finally, a sixth study [32] addresses forced disappearances in Colombia, focusing on the detection of clandestine graves of dismembered victims. By creating simulated graves and employing techniques such as multispectral imaging, electrical resistivity, and ground-penetrating radar, the effectiveness of these methods was evaluated, demonstrating that, despite the particularities of these graves, it is possible to detect them, representing an advance in the search for missing persons.

In 2023, five studies were published. The first, conducted in a nature reserve in the Middle East, addresses the location of clandestine graves in arid environments. Through a pilot test, soil temperature and moisture variations were evaluated using thermal images and statistical analysis, emphasizing the need for efficient methods and the use of UAV technology for non-invasive remote sensing in burial detection [33]. A second work classifies the applications of drones in forensic science, addressing the lack of structured reviews. Thirty studies (2012-2022) on the use of drones in crime scene investigation, clandestine grave detection, traffic accident investigation, disaster assistance, and pollution detection are summarized [34]. A third research article

focuses on a specific case: the search for a murdered minor buried in a rural forest. Best practices in geoforensic search are analyzed, highlighting a phased approach that optimizes resources and time, and describing remote sensing, geomorphological, and geophysical methods adapted to the case [35]. A fourth study addresses the detection of clandestine graves in Australia, where locating thousands of missing persons is a key challenge. Traditional techniques and advanced technologies such as ground-penetrating radar (GPR) and electrical resistivity tomography (ERT) were used, allowing the detection of soil disturbances without excavation. The need for a detailed technical protocol that considers soil conditions, equipment configuration, and data processing for effective use of this GPR and ERT combination is highlighted [36]. Finally, a fifth study focuses on the location of clandestine graves and proposes a multidisciplinary approach that combines forensic and geological knowledge and remote sensing techniques. Based on the analysis of grave searches in Italy, where a low success rate is revealed, a critical evaluation of current methods and the adoption of more modern approaches, such as remote sensing, are suggested, considering the factors that influence the choice of burial site [37].

In 2024, three research articles were published. The first [38], conducted in Poland, integrates historical, ethnographic, and archaeological methods, including non-intrusive remote sensing techniques, to investigate resettlement and prisoner-of-war camps from the two World Wars, seeking to discover material remains and their significance to contemporary society. A second study [39], conducted in Colombia, addresses the location of victims of forced disappearance, highlighting the need for effective forensic search methods. Existing geophysical techniques are employed and developed, with a multidisciplinary approach that includes the use of unmanned aerial vehicles (UAVs) to capture multispectral images, with the aim of evaluating the effectiveness of remote sensing and geophysical surveys in identifying graves between 4 and 8 years after burial. Finally, a third article [40] highlights that geoforensic methods offer non-invasive tools for locating clandestine burials and other evidence in criminal investigations. The geoforensic search strategy, with its preliminary, search, and subsequent phases, is based on the detection of subsurface anomalies. Techniques such as ground-penetrating radar (GPR), magnetometry, and electrical resistivity identify buried objects by detecting contrasts in their properties. The lack of a national geoforensic database and the need to standardize methodologies are noted as challenges to be overcome in India, although the potential of geoforensics to solve complex cases is recognized. The legal and ethical aspects associated with these techniques are emphasized, ensuring the accuracy, transparency, and admissibility of the results.

Table 1 presents the consulted research articles, ordered chronologically.

Table 1. Table of research articles, reports and books consulted reported in chronological order

Ref	Title	Authors	Year
[4]	Remote sensing-based assessment of hazards from glacier lake outbursts: A case study in the Swiss Alps	Christian Huggel, Andreas Kääb, Wilfried Haeberli, Philippe Teyssere, and Frank Paul	2002
[2]	Remote sensing as a tool for the detection of clandestine mass graves	M. Kalacska & L.S. Bell	2006
[7]	A comprehensive archaeological map of the world's largest preindustrial settlement complex at Angkor, Cambodia	Damian Evans, Christophe Pottier, Roland Fletcher, Scott Hensley, Ian Tapley, Anthony Milne, and Michael Barbetti	2007
[8]	Ground Penetrating Radar Advances in Subsurface Imaging for Archaeology	Dean Goodman, Kent Schneider, Salvatore Piro, Yasushi Nishimura, and Agamemnon G. Pantel	2007
[6]	Remote Sensing in Archaeology	JAMES WISEMAN and FAROUK EL-BAZ	2007
[9]	The application of remote sensing for detecting mass graves: An experimental animal case study from Costa Rica	Margaret E. Kalacska, Lynne S. Bell, G. Arturo Sanchez-Azofeifa and Terry Caelli	2009
[11]	The use of geoscience methods for terrestrial forensic searches	J.K. Pringle, A. Ruffell b, J.R. Jervis, L. Donnelly, J. McKinley, J. Hansen, R. Morgan, D. Pirrie, M. Harrison	2012
[10]	Cropmarks in main field crops enable the identification of a wide spectrum of buried features on archaeological sites in Central Europe	Martin Gajda and Michal Hejman	2012
[13]	Detection of single graves by airborne hyperspectral imaging	G. Leblanc, M. Kalacska, R. Soffer	2014
[12]	Prospecting for native metals in lunar polar craters	Warren J. Platts, Dale Boucher, G. Randall Gladstone	2014

Ref	Title	Authors	Year
[14]	Anthropology: Use of Forensic Archeology and Anthropology in the Search and Recovery of Buried Evidence	Blau, S. and Sterenberg, J.	2015
[17]	Geoarchaeology, Forensics, and the Prosecution of Saddam Hussein: A Case Study from the Iraq War (2003–2011)	Joseph Schuldenrein, Michael K. Trimble, Susan Malin-Boyce, and Mark Smith	2017
[16]	On the detectability of buried remains with hyperspectral measurements	Jesús Ariel Carrasco-Ochoa, José Francisco Martínez-Trinidad, José Arturo Olvera-López	2017
[15]	Remote sensing technology in forensic investigations: Geophysical techniques to locate clandestine graves and hidden evidence	G. Clark Davenport	2017
[19]	Survey and insights into unmanned aerial-vehicle-based detection and documentation of clandestine graves and human remains	Bryce Murray, Derek T. Anderson, Daniel J. Wescott, Robert Moorhead, and Melissa F. Anderson	2018
[20]	A novel application of terrestrial LIDAR to characterize elevation change at human grave surfaces in support of narrowing down possible unmarked grave locations	K.A. Corcoran, A.Z. Mundorff, D.A. White, W.L. Emch	2018
[21]	The application of low-altitude near-infrared aerial photography for detecting clandestine burials using a UAV and low-cost unmodified digital camera	Rykker Evers, Peter Masters	2018
[18]	Exploring non-invasive approaches to assist in the detection of clandestine human burials: developing a way forward	Blau, S., Sterenberg, J., Weeden, P., Urzedo, F., Wright, R., & Watson, C.	2018
[22]	A Low Cost Approach to Disturbed Soil Detection Using Low Altitude Digital Imagery from an Unmanned Aerial Vehicle	Parrott, E., Panter, H., Morrissey, J., & Bezombes, F.	2019
[23]	Remote and Close Range Sensing for the Automatic Identification and Characterization of Archaeological Looting. The Case of Peru	Masini, N., & Lasaponara, R.	2021
[24]	Forensic archaeology and forensic anthropology within Swedish law enforcement: current state and suggestions for future developments	Clara Alfsdotter	2021
[25]	Assessing optical remote sensing for grave detection	J.L. Silván-Cárdenas, A. Caccavari-Garza, M.E. Quinto-Sánchez, J.M. Madrigal-Gómez, E. Coronado-Juárez, D. Quiroz-Suarez	2021
[26]	Integrating Remote Sensing and Indigenous Archaeology to Locate Unmarked Graves A Case Study from Northern Alberta, Canada	William T. D. Wadsworth, Kisha Supernant, Ave Dersch	2021
[27]	Unraveling Crimes with Geology: As Geological and Geographical Evidence Related to Clandestine Graves May Assist the Judicial System	Somma, R., & Costa, N.	2022
[28]	Mapping Decomposition: A Preliminary Study of Non-Destructive Detection of Simulated body Fluids in the Shallow Subsurface	Barone, P. M., Matsentidi, D., Mollard, A., Kulengowska, N., & Mistry, M.	2022
[29]	Detection of Single Burials Using Multispectral Drone Data: Three Case Studies	Rocke, B., & Ruffell, A.	2022
[31]	Comparison of 3D models of mass graves created on the basis of aerial survey data in 1944 and 2015	B. Chetverikov, L. Babiy, Z. Kuzyk, I. Zayats	2022
[30]	Mapping a Poorhouse and Pauper Cemetery as Community Engaged Memory Work	April M. Beisaw, William P. Tatum III, Virginia “Ginny” Buechele, Brian G. McAdoo	2022
[32]	Monitoring of simulated clandestine graves of dismembered victims using UAVs, electrical tomography, and GPR over	Carlos Martín Molina, Kristopher Wisniewski, Vivienne Heaton, Jamie K. Pringle, Edier Fernando	2022

Ref	Title	Authors	Year
	one year to aid investigations of human rights violations in Colombia, South America	Avila, Luis Alberto Herrera, Jorge Guerrero, Miguel Saumett, Raúl Echeverry, Mario Duarte, Alejandra Baena	
[33]	The detection of clandestine graves in an arid environment using thermal imaging deployed from an unmanned aerial vehicle	Alawadhi, A., Eliopoulos, C., & Bezombes, F.	2023
[34]	A scoping review on drone technology applications in forensic science	Mohd Sabri, N. E., Chainchel Singh, M. K., Mahmood, M. S., Khoo, L. S., Mohd Yusof, M. Y. P., Heo, C. C., Muhammad Nasir, M. D. M., & Nawawi, H.	2023
[35]	Historic child homicide burial search in rural woodland	Pringle, J. K., Ruffell, A., Wisniewski, K. D., Davenport, B., Heaton, V., & Hobson, L.	2023
[36]	A technical protocol for using ground penetrating radar and electrical resistivity tomography in the search for covert graves	Victoria Berezowski, Xanthé Mallett, Isabella Crebert, Dilan Seckiner, Justin Ellis and Ian Moffat	2023
[37]	Forensic Geology Applied To The Search For Homicide Graves	Roberta Somma, Lerah Sutton And Jason H. Byrd	2023
[38]	Searching for the Missing Graves of PoWs from the Second World War—an Example of Research Conducted in the Area of Stalag VIII B (344) Lamsdorf	Kobiałka, D., Michalski, M., Karski, K., Lokś, A., Pawleta, M., Rezler-Wasielewska, V., Wroniecki, P., Wysocka, J., & Czarnik, M.	2024
[40]	Geoforensic Methods for Detecting Clandestine Graves and Buried Forensic Objects in Criminal Investigations - A Review	Narreddy, Vaishnavi	2024

Figure 2 shows the temporal evolution of publications. Growth in the scientific production related to the topic of study is observed, with a significant increase starting in 2018.

The linear trend line in Figure 2 indicates an approximately constant increase in production over time. Years with no publications are observed. Overall, the graph shows sustained growth in the field of remote sensing applied to forensic science, reflecting increased interest and development in this area.

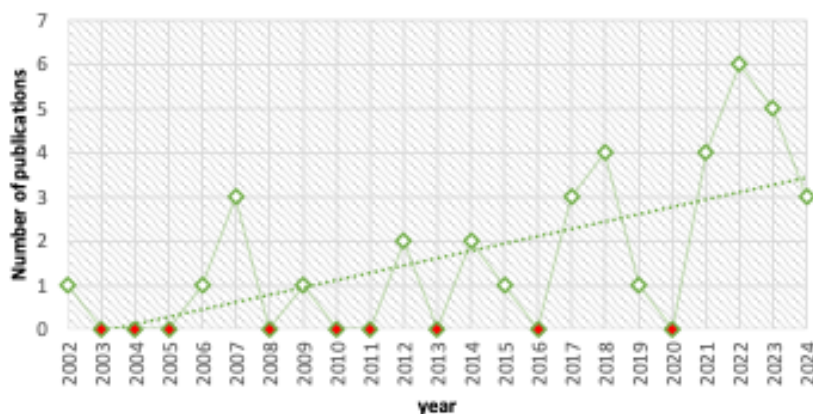


Figure 2. Graph depicting the number of publications per year for research articles related to remote sensing and forensic scenarios

3.1. Techniques reported in the literature

The consulted investigations employ a variety of methods, primarily based on remote sensing, with a multidisciplinary approach. This approach allows obtaining crucial data for interpretation in forensic science. The specific methods are described below, highlighting their relevance and application.

Remote sensing, primarily through satellite and unmanned aerial vehicle (UAV) imagery, is fundamental in all reviewed investigations. Multispectral and RGB data are used to analyze areas of interest. Additionally, Geographic Information Systems (GIS) are employed to manage and analyze spatial data, and LiDAR to obtain three-dimensional models of the terrain. The multidisciplinary approach is reinforced with

the application of geophysical techniques, such as electrical resistivity tomography (ERT) and ground-penetrating radar (GPR), as well as with geomorphological analysis and the study of vegetation properties.

Multispectral and hyperspectral imagery play a crucial role in forensic science, especially when combined with other techniques. For example, spectral indices, along with geophysical methods, are used to improve the detection of clandestine burials. Barone *et al.* [28] simulated a burial using saline solutions to replicate body fluids. Ground-penetrating radar (GPR) detected alterations in the dielectric constant of the subsurface, indicating the presence of the fluids. Additionally, satellite imagery (using the NDVI index) and drone imagery (using the VARI index) were used to assess the detectability of anomalies related to the burial.

Geophysical methods, such as magnetometry, electrical resistivity, and ground-penetrating radar (GPR), are essential tools in forensic investigation for locating human remains and buried evidence without the need for invasive excavations [11], [14], [26], [36]. GPR, in particular, generates subsurface images that reveal hidden structures, such as clandestine graves and unmarked tombs. Electrical resistivity tomography (ERT) complements this information, providing a subsurface profile that helps to understand its composition and structure. The combination of GPR and ERT, along with the appropriate selection of parameters and data processing, optimizes the effectiveness of surveys. Furthermore, as previously seen, the integration of these methods with remote sensing allows the identification of potential burial sites on a large scale [14], [17].

Both multispectral and hyperspectral imagery, obtained via satellites and drones, are key tools in the search and documentation of clandestine graves and human remains [5], [9], [16], [19], [25], [32]. The high spectral resolution of hyperspectral imagery, in particular, allows the detection of subtle changes in surface reflectance, and spectral indices derived from these images help to identify alterations in vegetation caused by decomposition. Multispectral imagery, although with lower spectral resolution, is also effective, especially when combined with other remote sensing and analysis techniques [16], [19], [25], [32].

One study [29] used a Sentra 6x multispectral sensor mounted on a drone to capture data at specific sites, at a predetermined altitude. Spectral indices such as NDVI, GNDVI, VARI, and NDRE, chosen for their sensitivity to vegetation health and density, were applied to analyze soil disturbances and vegetation changes related to burials. Another investigation [39] simulated burials in savanna and rainforest ecosystems in Colombia, using human and pig remains. These burials were monitored over time, employing drones to collect multispectral imagery and applying indices such as NDVI, VARI, GCI, SIPI, and GLI to evaluate their effectiveness in different soil types and depths.

LiDAR technology, due to its high precision in detecting subtle changes in terrain elevation, is another key tool in the identification of clandestine burials [18], [20]. One study [18] used LiDAR, along with UAVs equipped with multispectral sensors, on experimental graves containing human remains to model terrain alterations over time. Another study [20] employed terrestrial LiDAR to detect unmarked graves, identifying the elevation changes characteristic of these burials.

In addition to the techniques already mentioned, thermal imaging and statistical analysis are used to detect clandestine burials. In a study in Kuwait [33], a plot was selected in the Jahra Pools nature reserve, burials were simulated in two graves, and changes in soil temperature and moisture were evaluated over 18 months. Thermal images were captured at different heights and times, and temperature variations and soil moisture indices were analyzed.

3.2. Results reported

The techniques described, such as spectral index analysis, thermal imaging, geophysical methods, and LiDAR technology, have enabled the identification and characterization of areas of forensic interest, such as clandestine graves and human remains. The most relevant findings are presented below.

3.2.1. Multispectral imaging and spectral indices

The processing of multispectral and hyperspectral imagery, and the use of spectral indices, revealed that several studies highlight the Normalized Difference Vegetation Index (NDVI). Table 2 presents a list of the spectral indices used and their equations

In the study conducted in Colombia [39], the use of multispectral imagery obtained with drones allowed the identification of seven of the eight simulated graves. This demonstrates the usefulness of NDVI for detecting vegetation disturbances. However, deeper graves were more difficult to detect, indicating limitations in detection capability at greater depths. Figure 3 shows the results of the eight burials in the savanna, with views of different spectral indices.

NDVI analysis allowed the detection of vegetation anomalies, providing information about the time of burial. The VARI index also revealed vegetation stress near the burial site, demonstrating its potential for detecting anomalies in aerial imagery [28].

Another study [29] highlights the use of GNDVI, which, along with NDVI, was effective in revealing burial sites. In this study, graves dating back to 2016 were identified at three sites, confirming that soil composition and burial depth significantly influence microbial activity, nutrient release, and, therefore,

vegetation growth and recovery patterns. Figure 4 shows the results, evidencing the use of spectral indices to observe burial patterns.

Table 2. Spectral indices used and their equations

Index	Formula
GLI (Green leaf index)	$GLI = \frac{(GRREN - RED) + (GREEN - BLUE)}{(2 * GREEN) + RED + BLUE}$
GCI (Green chlorophyll index)	$GCI = \frac{NIR}{GREEN} - 1$
SIPI (Structure insensitive pigmentation index)	$SIPI = \frac{NIR - BLUE}{NIR - RED}$
VARI (visible atmospheric resistance index)	$VARI = \frac{GREEN - RED}{GREEN + RED - BLUE}$
NDRE (red border with normalized difference)	$NDRE = \frac{RED\ EDGE - RED}{RED\ EDGE + RED}$
GNDVI (normalized green difference vegetation index)	$GNDVI = \frac{NIR - GREEN}{NIR + GREEN}$
NDVI (normalized differential vegetation index)	$NDVI = \frac{NIR - RED}{NIR + RED}$

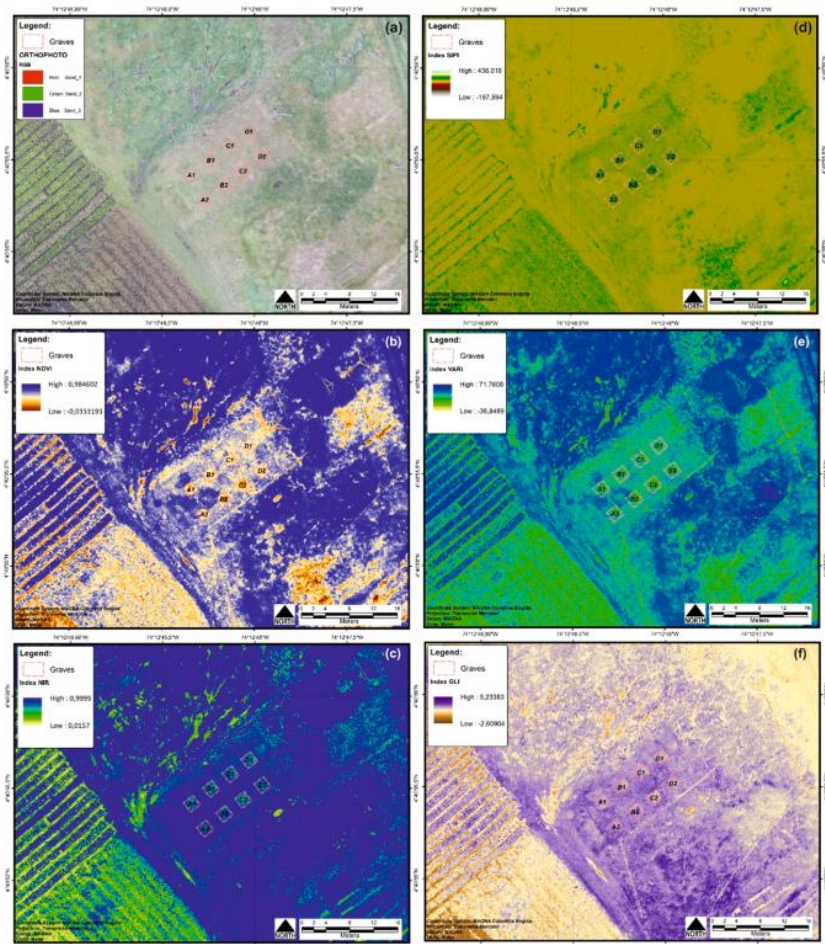


Figure 3. UAV drone processed multi-spectral images of site 1 taken at 70 m height 3030 days post-burial (Table 2). (a) ortho-photomosaic image and, (b) NDVI, (c) NIR, (d) SIPI, (e) VARI and (f) GCI multi-spectral images (see text for details) [39].

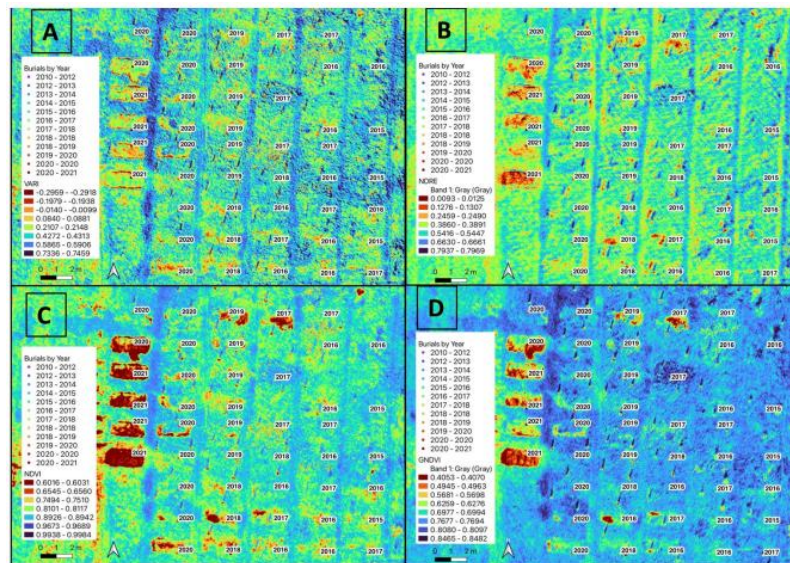


Figure 4. Site 1 Vegetative Index maps include VARI (A), NDRE (B), NDVI (C), and GNDVI (D). The full range of index values is constrained to highlight localised differences. NDVI shows single graves most clearly, with younger graves to the left (2021) and older graves to the right (2016). NDRE has the poorest single grave resolution [29].

3.2.2. Geophysical methods

Electrical resistivity tomography (ERT) data indicate that, over time, the electrical conductivity of the soil around burials tends to homogenize with that of the surrounding areas, making detection difficult [39]. Although high resistivity anomalies may be observed initially, this differentiation decreases over time.

The electrical resistivity tomography ERT results show that, while some burials are detectable shortly after they are made, the ability to locate them decreases significantly after several years. The need to carefully interpret the data is emphasized, as anomalies do not always correlate with the actual location of the burials [39].

Ground penetrating radar GPR data collected over time reveal difficulties in identifying the precise location of burials, particularly after several years [39]. However, GPR scans can identify subsurface features that, while not always corresponding directly to burials, allow targeted excavations. For example, one study [28] showed that GPR can reveal the movement of fluids in the subsurface, influenced by soil composition and environmental factors.

3.2.3. LiDAR data

LiDAR technology, due to its precision, allows the identification of burial area contours and landscape changes over time, which is useful in forensic investigations [18].

3.2.4. Thermal imagery

The study that used thermal imaging [33] found that: The temperature of the experimental grave (with remains) was consistently higher than that of the control grave for the first ten months. The largest temperature difference (3.3°C) was recorded in the seventh month. Both graves remained cooler than the surrounding area, except in the third month, when the experimental grave exceeded the temperature of both the control and the surroundings. A two-way ANOVA evaluated the effects of drone height and the presence of remains on temperature. Drone height had an insignificant effect ($p=0.985$), while the presence of remains had a significant influence ($p=0.005$).

4. DISCUSSION

The findings indicate that thermal images obtained with drones are effective for detecting recent graves in arid climates, thanks to observable temperature and humidity variations for several months. However, the sample size and environmental factors limit the generalization of these results, so more research is needed with larger graves and in different conditions. The challenges in detecting individual graves (more difficult to identify than mass graves) are also highlighted. Future research should focus on integrating detection methods, exploring the influence of environmental factors, and collaborating with disciplines such as botany to investigate vegetation alterations. Although remote sensing with drones and multispectral data was effective, optical photography was less so. The importance of combining techniques to improve detection over time is

emphasized, and caution is advised when using drone-based remote sensing in areas of very dense vegetation. Finally, it is established that positive results are more frequent in short periods, indicating the need to research methods for detecting older burials (>10 years).

The investigations highlight innovative methods and techniques for the detection of clandestine graves in forensic contexts. The effectiveness and cost-effectiveness of drone-based methodologies are emphasized, as well as the importance of a multidisciplinary approach that combines multispectral and thermal imagery, LiDAR data, and geophysical methods. NDVI, in particular, is useful for detecting burial areas, but its application must be adapted to various ecosystems. In summary, remote sensing, especially with drones, contributes significantly to forensic science.

Future research in this domain must pivot towards the integration of Artificial Intelligence (AI) and Machine Learning (ML) algorithms to automate the detection of subtle soil and vegetation anomalies, thereby reducing the reliance on manual image interpretation. Furthermore, there is a critical need for longitudinal studies across diverse biomes to better understand the temporal dynamics of taphonomic spectral signatures, particularly for burials older than ten years. We also predict a shift towards the development of standardized, open-access forensic spectral libraries and the use of multi-sensor fusion (e.g., LiDAR combined with hyperspectral imaging) on agile UAV platforms to enhance detection probabilities in complex, vegetation-dense environments.

5. CONCLUSIONS

In conclusion, remote sensing has emerged as a transformative tool in forensic science, shifting the paradigm from invasive manual searches to efficient, wide-area non-destructive assessments. This review highlights that while no single sensor offers a universal solution, the multidisciplinary integration of UAV-based multispectral and thermal imaging with geophysical methods—such as GPR and ERT—significantly increases the probability of locating clandestine graves. Although challenges remain regarding burial depth and time-since-death detectability, the increasing accessibility of these technologies offers a viable protocol for optimizing forensic investigations. Ultimately, the adoption of these remote sensing techniques contributes not only to procedural efficiency but also to the humanitarian goal of dignified recovery and truth-seeking.

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