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Where are they? A review of statistical techniques and data analysis to support the search for missing persons and the new field of data-based disappearance analysis

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A R T I C L E I N F O

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A B S T R A C T

The disappearances of individuals are complex phenomena, spanning different regions and temporal periods. Evolving from different legal, social, and forensic disciplines, existing research has signaled the reasons for and contexts in which people disappear or go missing, as well as the development of investigative tools that assist, in fatal cases, in their identification. However, a different type of applied research, which we have labeled as data-based disappearance analysis (DDA), can offer statistical techniques to support the search for missing persons. In this paper, we review the literature on DDA, paying close attention to the evolution of this methodology and its contextual relevance. We highlight three applications by which DDA may support the search for missing persons: statistical inference, geospatial tools, and machine learning models and artificial intelligence. We demonstrate significant results using these applications, the potential misuses and ethical concerns, and draw lessons from their use. Lastly, we make recommendations to help researchers and practitioners support the search for missing persons.

1. Introduction

An individual may go missing due to a multitude of factors, including violence, social and political problems, and natural disasters. Studies have typically focused on understanding the reasons why people disappear [27], highlighting their possible connection to human rights violations or international crimes, and developing forensic techniques to identify missing persons in humanitarian contexts [55,69,91]. Some research focuses instead on documenting disappearances as part of social and judicial processes aimed at addressing past atrocities during armed conflicts or authoritarian rule [8,19,37,54,75,90]. However, more recently, statistical and geospatial tools have been used to complement traditional methodologies for the search for missing persons. Despite being used in the 1990s to identify patterns of disappearances during armed conflict and to estimate the numbers of casualties in armed conflicts, advances in computational capabilities and methods from geospatial sciences, machine learning, and artificial intelligence have demonstrated significant benefits of data analysis in these contexts. Notably, as we argue below, these technologies can help answer the question of where to look for the missing people and help elucidate the circumstances of their disappearance.

Thus far, there has not been a systematic effort to identify the evolution and application of disappearance analysis using data-based methods. In this article, we present the first critical review of the literature on and methodology for the use of statistical technologies in the search for missing persons, which we refer to as "data-based disappearance analysis" (DDA). We argue that three areas of statistical application and data analysis can support the search for missing people: statistical inference, geospatial tools, and machine learning models and artificial intelligence. We identify the advances and limitations of these areas and propose a series of recommendations to advance this field.

In Section 2, we discuss the conceptualization and definitions of

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"missing people" and "disappearances," clarifying how their study has been approached in light of the spatiotemporal contexts of these events. In Section 3, we show the evolution of search technologies through case studies. In Section 4, we discuss the potential misuses and ethical concerns related to DDA, and in Section 5 we identify lessons learned from the use of these tools and provide some recommendations for further efforts to locate the missing. In the conclusion, we synthesize the findings of this article.

2. The phenomenon of missing people: rationale, place, and time

Disappearances are complex events due to the diversity of circumstances from which they can arise [26,37,75]. When studying disappearances, it is essential to differentiate between cases believed to be related to violence and those that are not [26]. Violence-related cases are usually considered either *enforced* disappearances or *involuntary* disappearances in international humanitarian, criminal, and human rights law [75]. Enforced disappearances are characterized by three cumulative elements: a person is deprived of their liberty against their will, with the participation of the State or private agents with the acquiescence of the State, and with refusal by the aforementioned parties to acknowledge the deprivation of the person or to disclose their whereabouts [93]. Involuntary disappearances satisfy the first and third conditions, but the perpetrator is, importantly, a non-state agent, acting *without* (the acquiescence of) the State.[2]

Non-violent disappearances are cases in which individuals are not abducted against their will or through a violent, criminal act [26].[3] These cases are often associated with natural disasters or other factors, such as neurodegenerative diseases, which can cause memory lapses and spatial confusion [17]. Given these differences, it is essential to note that, in this article, the term "disappearances" refers to cases of criminal or State violence [26], whereas the term "missing persons" is broader, encompassing cases arising from other, non-violent circumstances [26].

Searches for missing persons typically involve considering different possible scenarios. Once the likeliest cause has been ascertained, the most appropriate strategy to resolve the disappearance can be adopted. Various approaches exist depending on whether the individual is believed to be alive or dead. When efforts are directed at finding the individual alive, searches are conducted in locations such as hospitals, detention centers, and other public institutions; otherwise, efforts are made to recover corpses in clandestine graves,[4] mortuaries, or public cemeteries. In more complex scenarios, the physical location of the missing person is known, but their identity still needs to be corroborated by authorities and relatives [26,96]. Thus, it is essential to acknowledge that search efforts may also be related to criminal investigations or simply directed at formally identifying an individual's remains. The search for people on humanitarian grounds is typically distinguished from searches whose primary objective is criminal prosecution [69,83], although some argue that this distinction is problematic (e.g., [65]). Search strategies also involve a temporal dimension, which differs depending on whether a case is considered "recent" (i.e., days or weeks) or the person's whereabouts have been unknown for a more extended period (i.e., several years). The recency of the events does not determine *per se* whether the case is associated with a violent act, but it could impact decisions to prosecute those responsible for disappearances.[5]

3. Technologies to support the search for disappeared people: using statistics and data analysis in the field

Statistics and data analysis technologies have been developed to estimate the magnitude of disappearances [65]. Geospatial analysis and forensic tools have been deployed to locate sites that contain the bodies of missing persons. And machine learning and artificial intelligence techniques have been implemented to classify the status of a missing person.[6] These three technologies facilitate searches for victims of disappearances who are believed to have died. Recent machine learning and artificial intelligence implementations also present potential solutions to support search strategies for individuals presumed to be still alive. Due to the many variables that must be considered, in this article we have limited our review to three DDA approaches that can be used to locate victims of enforced or involuntary disappearance.[7] We made this decision based on the historical evolution of these three approaches, which are the most established in the field. Other methodologies are deemed ineligible, especially when their aim is purely descriptive [10], non-inferential or non-predictive, or if they do not rely on multiple geographical and social dimensions. Furthermore, other technologies do not necessarily use statistical analysis to pinpoint the location of victims of disappearances, but rather, to facilitate other processes, such as forensic identification [55,91].

3.1. Statistical inference

The use of statistics to facilitate the search for the disappeared began in the 1990s, when it was initially employed to estimate the magnitude of this phenomenon within the context of armed conflict or generalized human rights violations. In other words, these methods were not initially used to identify locations where disappearances may have occurred or to predict the status of disappeared persons, but rather to estimate the absolute number of people who had disappeared.[8] These approximations have been—and continue to be—used to identify the patterns of registration or production of information surrounding the phenomenon, as well as the associated biases. Bias in this context refers to the fact that no registries accurately capture the actual population of disappearances, due to geographical, political, or economic limitations imposed on the institutions that compile the datasets [56]. Both official databases and unofficial records related to violence use convenience samples [10].

The first studies to employ statistical techniques were conducted in El Salvador in the 1990s, following the signing of peace agreements that ended the armed civil conflict (1960–1996) [14]. These studies were

[2] These definitions are not exempt from debate, especially since the differences between State and Non-state actors can be unclear. Above all, in "Hybrid States," disappearances are committed through collusion among, or collaboration between, both types of perpetrators (See: [20,83,84]).

[3] There may be other acts or phenomena of violence that make a person's whereabouts unknown. These events may be kidnapings, human trafficking, or forced recruitment.

[4] In this text, mass graves, clandestine graves, and burial sites will be used interchangeably. However, an overview of the typologies and definitions related to them can be seen in [49,53,69,88].

[5] The events are still considered disappearances if they meet the three cumulative elements from the definition provided. This applies even if the whereabouts of the person who disappeared becomes known after a specific period. (See: [63,71]).

[6] In distinguishing between these three approaches, we do not mean to overlook the overlapping uses of these tools. For example, inferential statistical techniques can use machine-learning techniques to impute missing values. Likewise, the combination of spatial analysis and machine learning in classification scenarios is becoming more common.

[7] Other technologies are associated with identifying the bodies of disappeared persons upon their recovery, such as the use of software and statistical techniques to identify the remains of people through DNA techniques [22,67]. However, these technologies are outside the scope of this work.

[8] An important possible exception may be found in Snow and Bihurriet [80]. Their search was smaller-scale, discerning the identity of disappearance victims among the burials of unidentified persons within a cemetery.

fundamental because, for the first time, records of human rights violations were understood not only as bibliographic references[9] but also as sources of quantitative information that could be used to resolve cases [15]. This led to the development of the first methodologies for recording human rights violations in ways that made them analyzable using quantitative methods [9,12,61,85]. Subsequently, techniques were developed to combine the records from different sources that documented victims of murders or disappearances. This had two objectives: first, to identify the total number of victims who had been registered exclusively by a registry or database, as well as those who had been documented by distinct institutions or organizations; and second, to estimate the number of people who were *not* documented by any available registries or databases.

Various techniques exist for identifying whether multiple sources of information have documented the same individual. These techniques are known as "record linkage," and their capacities range from manually deciding whether multiple records correspond to the same victim (i.e., pairwise record linkage) to using machine learning techniques to match the names of individuals through previously trained labels (i.e., supervised record linkage) [15].

The number of victims of homicides and disappearances not documented by any databases or conflict records can be estimated using a statistical technique known as Multiple Systems Estimations (MSE). Also known as *capture-recapture*, "MSE refers to a class of methods that use multiple samples with unknown sampling probabilities to estimate the size of populations" ([15], p. 71). The main challenge in using MSE is that it requires two or more lists or registries to conduct the estimates of disappearances. If analysts have only two lists, strong assumptions are required, such as the independence of the systems and that every member of the population has the same probability of inclusion [15,56]. Newer methods require weaker assumptions, and it is also recommended that at least three independent lists or registries be used when conducting MSE.

MSE has proved statistically effective in demonstrating the scale of human rights violations and international crimes in contexts such as the Guatemalan Civil War (1960–1996) [14], the genocide in former Yugoslavia (1992–1995) [5], the internal armed conflict in Perú (1980–2000) [11], and the internal armed conflict in Timor-Leste (1974–1999) [76].[10] It has also been used to estimate the number of disappearances in Sri Lanka during the last days of the civil war in 2009 [13], and the total number of homicides, disappearances, kidnapings, forced displacements, and forced recruitment of minors in Colombia between 1985 and 2018, forming part of the efforts of the Commission for the Clarification of Truth, Coexistence, and Non-repetition in Colombia [50] (Figs. 1–3).

3.2. Geospatial technologies and forensic tools

In the search for disappeared persons, geospatial technologies enable the visualization, analysis, and reconstruction of the context surrounding a disappearance. They also make it possible to infer the *modus operandi* of the perpetrators, map the area(s) where bodies or remains have been located (including clandestine or mass graves), and generate predictive spatial models that can identify potential body disposal sites. Theoretical frameworks from behavioral ecology and environmental criminology have lent themselves to the development of spatial and predictive modeling, establishing that "humans interact with their environments in patterned, non-random ways" ([29], p. 263).

The mapping of possible search sites can be conducted using various spatial proxies through deductive and inductive methods, enabling the modeling of perpetrators' behavior and their interactions with victims and their environment [29]. Studies employing these methods have used spatial statistics, combining layers of vector and raster data to map the relationship between locations from which people have disappeared and other spatial and cultural variables, such as roads, borders, and proximity to urban sites. In cases of multiple or systematic disappearances, studies can begin by identifying significant clusters of killing sites, such as clandestine graves, using hotspot analysis, average nearest neighbors (ANN), or Ripley's K function [29]. Parametric and non-parametric tests, such as Chi-square Goodness of Fit or the Mann-Whitney *U* test [29], can be used to test statistical significance.

For example, Congram [25] used the coordinates of known clandestine graves of victims and studied the dynamics of the perpetrators of the Spanish Nationalist rebels and postwar violence (1936–1942) to map areas where other burial sites could be located in the Castilla y León region with the objective that this methodology could be used to find more missing persons. Likewise, Congram et al. [28] identified the patterns in clusters of mass graves located in the former Yugoslavia to estimate areas where new graves could be located based on the spatial distribution of already mapped points. Santillán [74] conducted a study on the spatial characteristics of mass graves in Guatemala created during the period of armed civil conflict (1960–1980). Finally, descriptive spatial statistics have been used to characterize regions where migrant bodies have been located in the United States, in Arizona[11] [42], as well as the sites where remains of murdered people have been located in Florida [52]. Studies in both states, although descriptive, might be essential for identifying social and geographical variables that influence the recovery of bodies of missing persons.

Other studies have combined spatial layers—such as vegetation type, terrain elevation, and visibility—with the analysis of vector or point data. For example, Ruffell and McAllister [70] used a Red, Amber, Green (RAG) System to classify potential exhumation sites, based on specific archeological criteria exemplified in historical graveyards. Somma et al. [82] combined vector and raster layers of variables, such as geomorphology and visibility, to develop an RAG System to classify areas with potential clandestine graves of murder victims in Italy. This study was conducted on simulated graves and has not been deployed in real-life search scenarios.

Other modeling and predictive techniques combine layers, satellite images, and historical maps. In Colombia, as part of the search for victims of the armed conflict (1985–2018), the EQUITAS team used a tool from the natural sciences known as the Maximum Entropy Model (MAXENT), which was designed to identify the distribution of species and their environments [35]. Their model was created for the Casanare region in Colombia to narrow down potential search areas for new clandestine graves based on the distribution of previous findings and relative to places of known combatant activity [36]. Nevertheless, the Colombian example illustrates one of the limitations of this method, as academic or civil society organizations often lack the authority to test their methods and confirm or refute their findings.

In Mexico, in the context of violence engendered by the state-sanctioned use of armed forces to counter drug-related activities since 2006, spatial statistics have been combined with theory derived from environmental criminology to identify possible sites of clandestine graves in Guerrero, Mexico [77]. Point pattern analysis and hyperspectral analysis with satellite images have also been used to identify anomalies in nitrogen concentration in the Baja California region, indicating areas where clandestine graves might be located [2,78]. In contrast to the Colombian example, this combination of spatial statistics and satellite imaging has proven effective in supporting civil society-led

[9] For a study examining the use of these registries as political tools and memory uses, see Bernasconi [19].

[10] MSE has also been used by Cruyff et al. [30] to estimate the number of human trafficking victims in the Netherlands from 2010 to 2015.

[11] We include this study because many of the migrants are considered "missing" since their relatives or close associates do not possess information regarding their whereabouts, nor do they know whether or not the individual has died.

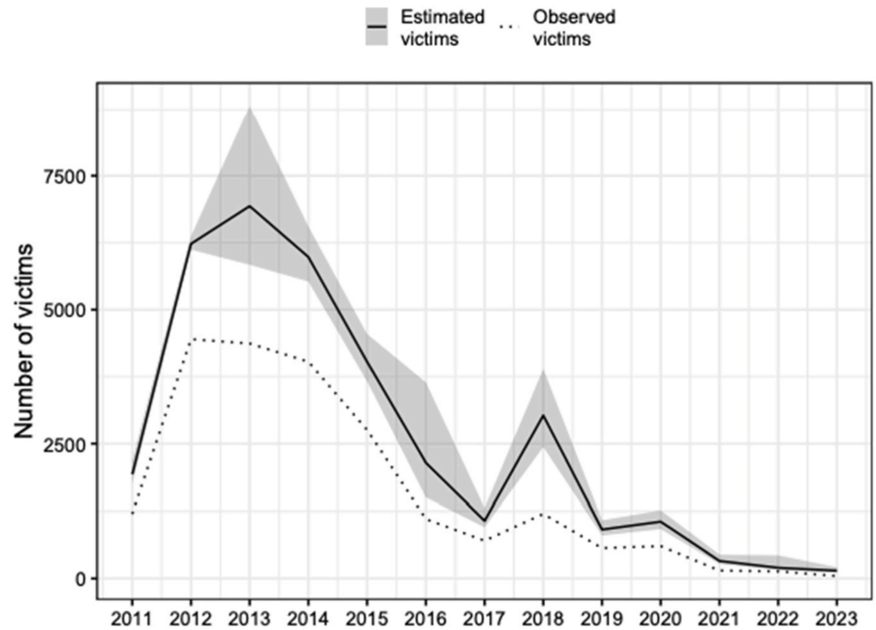

Fig. 1. *Example of estimated deaths in custody in Syria between 2011 and 2023, using Multiple Systems Estimation (MSE). Note*. Research utilized eight sources of information that documented victims who were killed in custody in Syria between 2011 and 2023. These sources were used to estimate the size of the total victim population. From "Deaths in custody during the armed conflict in Syria, 2011–2023", by M. Gargiulo, T. Shah, and M. Price, 2024, *Human Rights Data Analysis Group* (HRDAG), p.12 https://hrdag.org/report/20241210-deaths-in-custody.pdf.

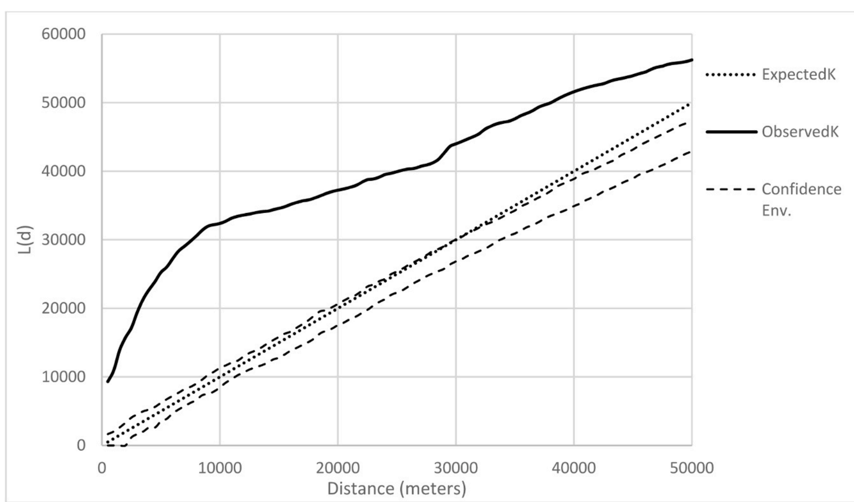

Fig. 2. *Example of Ripley's K function to analyze clustering of burial location during 1991–1993 in Bosnia and Herzegovina.* Note. The graph shows significant clustering of burial locations in Bosnia and Herzegovina at a 10 km radius. The results indicate that future searches should prioritize the 8–9.5 km range around known graves based on Ripley's K Function. From "Mapping the Missing: A New Approach to Locating Missing Persons Burial Locations in Armed Conflict Studies", by D. Congram, A. Green, and H. Tuller, 2016, *Missing Persons. Multidisciplinary Perspectives on the Disappeared*, Canadian Scholar's Press, p. 219.

terrain search brigades in the northernmost Mexican State. In April 2023, researchers involved in this project provided information on potential search areas, culminating in two positive findings of clandestine graves [48,72]. The UN's Working Group on Enforced or Involuntary Disappearances has also recognized this approach for its results [94]. Forensic Architecture conducted research in Louisiana, United States, examining environmental racism and possible burial sites for previously enslaved people in the area. They employed a technique known as cartographic regression to superimpose historical censuses, maps, and area images, thereby generating probability fields for the location of these burial sites [39]. The results of this study have yet to be tested in the field.

Finally, the use of satellite images or remote sensing has proven helpful for investigations into human rights violations and international crimes [43]. The evidence obtained through remote sensing includes the identification of areas with potential mass graves and can be effective when access to the ground is not possible due to security risks [33,66]. For example, these images have been used to document the genocide perpetrated in Myanmar between 2017 and 2021 [66] and the Russian invasion of Ukraine that began in February 2022 [68,92]. Satellite images also revealed new mass graves in two small villages east of Adwa, in Ethiopia's Tigray region, in October 2022. An on-site inspection of the area confirmed the findings [51].

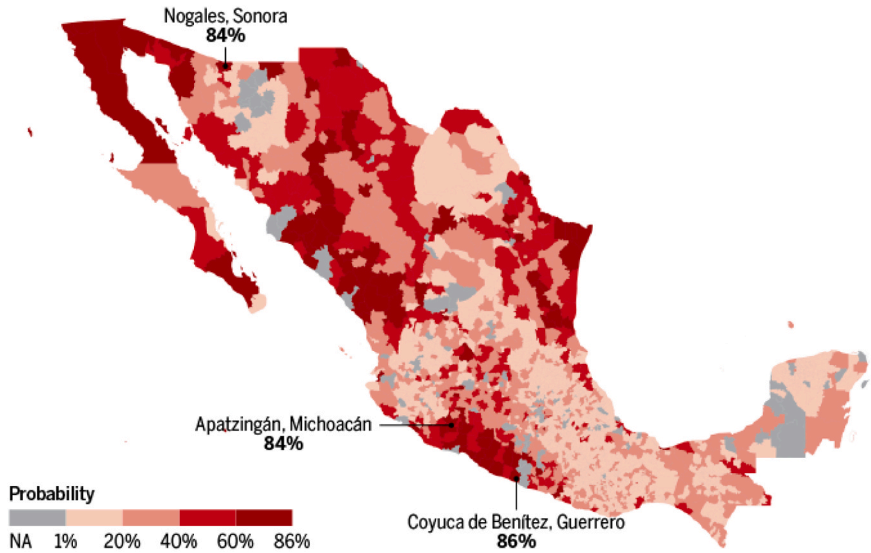

Fig. 3. *Map showing municipalities in Mexico that were most likely to contain hidden graves in 2016.* Note. The map displays the results of a machine-learning algorithm that predicted the locations of unobserved clandestine graves in Mexican municipalities, based on official and press reports. The model used approximately 40 covariates to classify the municipalities. From "Mapping Mexico's hidden graves. Statistical model could guide future searches for the disappeared", by L. Wade, 2017, *Science*, https://www.science.org/content/article/mapping-mexico-s-hidden-graves.

3.3. Complex networks and machine learning/AI implementations

Other approaches have recently been developed to support the search for missing persons, leveraging advances in network theory, machine learning, and artificial intelligence. These tools have been applied to historical and recent missing persons cases in which the status of the individual (i.e., alive or dead) is unknown. These applications also have the potential to support the distinct search strategies required for both (forcibly) "disappeared" and (accidentally or self-imposed) "missing" people. However, most of these approaches remain experimental, and real-world implementations with successful results remain limited.

In Argentina, the Argentine Forensic Anthropology Team (EAAF, in Spanish) has offered a framework to identify Illegal Detention Centers (IDCs) in the Tucumán region, where it is suspected that the remains of individuals who were forcibly disappeared during the dictatorship (1976–1983) might be located [23]. The EAAF has established networks with nodes corresponding to individual missing persons, each with unique attributes. By examining network clusters, the study identifies sites where victims who have not yet been located might be found, based on the proximity of these disappeared persons to other individuals whose remains were found in the IDCs at the time of their disappearance.

Innovative applications of machine learning and artificial intelligence have also been used in studies to predict locations for the placement of clandestine graves. Conducted in Mexico, these investigations differ from the approximations made using Geographic Information Systems (GIS), focusing instead on identifying municipalities in the country with characteristics similar to those previously reported to contain graves. These studies are unique in their predictive power, enabling the generation of nationwide predictions and the detection of biases inherent in the sources—both official and unofficial—that produce information about disappearances in Mexico [66]. These studies have been used in advocacy efforts by civil society, targeting authorities in charge of search efforts, rather than being applied in the field [31].

The applications of machine learning and artificial intelligence enable a change in focus: from classifying scenarios in which missing persons have lost their lives (for example, in the location of clandestine graves), to facilitating the search for the living by identifying fine-grained characteristics of missing persons.[12] Similar studies have been carried out using machine learning algorithms to predict cases of human trafficking in India [24] and to classify cases of human trafficking online [4]. Neither of these studies' results has been used in real-life scenarios. In Colombia, Ruiz-Rizzo et al. [73] developed a machine learning model to predict whether a person reported missing will be found alive. The authors of this study specify that their sample represents individuals over sixty years of age who have gone missing for reasons unrelated to violence. As in the aforementioned case, the findings of this study have not been validated in real-life scenarios. However, the methods of this study can be adapted to predict the outcomes of violence-related cases and are thus relevant to our review.

Solaiman et al. [81] developed a multimodal model to support searches for missing persons in the United States. Their approach analyzes heterogeneous information sources, such as images or text containing information about people whose whereabouts are unknown. Their model supports the search efforts of authorities by analyzing videos or images of people with characteristics like those of individuals whose information is available (i.e., hair color, height, last clothing description). As with the previously mentioned study, the results have not been implemented in real-life scenarios, so they remain experimental, as recognized by the authors.

Finally, machine-learning approaches have also been used to support the classification of large volumes of information related to disappearances, exemplifying other potential real-world applications. For example, in Colombia, the Human Rights Data Analysis Group utilized machine-learning models to impute missing data from over 100 datasets containing information related to disappearances and other human rights violations documented during the armed conflict in Colombia

[12] The documentation and quality of the information obtained are fundamental to obtaining these characteristics, which may include personally identifiable data, biological background, social history/lifestyle, and details about the circumstances of the disappearance [47].

(1985–2018) [50].

Table 1 summarizes the DDA techniques reviewed in this section.

4. Potential misuses and ethical considerations in DDA

Despite their emerging potential, statistical and data-driven approaches also introduce new potential or actual harms in social contexts [6,7,60,62,64]. Data-based disappearance analysis may not be exempt from these issues, and analysts and practitioners should be aware of the potential biases, misuses, and ethical considerations associated with the implemented technologies.

As highlighted in Section 3.1, DDA approaches should always consider and identify ways to tackle potential data bias. As we discussed, violence-related data are always incomplete; official institutions or citizen-led initiatives are never able to fully document the phenomenon due to economic, social, or political constraints [56]. Thus, inferential or predictive approaches should be aware of these biases and understand the limitations and context of the data [32].

Privacy and the sensitivity of the data should also be given serious consideration. Usually, data associated with disappearances contains information related to the victims, their families, and even suspected or actual perpetrators of the crimes. These data could include names, ages, and even DNA data.[13] This means that processes related to the search for the missing could lead to an intrusion into the person's privacy [40] and analysts should avoid creating more harm to those who are often already vulnerable, considering the possible negative impacts of using this type of data.

Furthermore, institutions and organizations responsible for gathering and analyzing information on disappearances should establish and adhere to proper data governance and ethical frameworks. Data governance is defined as the "practice of establishing and implementing policies, procedures, and standards for developing, using, and managing the infosphere" ([38], p.3). Good and ethical data governance is fundamental, imparting individual responsibility to stakeholders regarding the generation, preservation, and security of the data they produce to guarantee the implementation of agreed-upon standards and to, for example, guarantee privacy, data protection, and the secure exchange of information between actors [1,3,57].

There are examples of good practices of data governance frameworks in DDA, although they remain limited. For example, the International Committee of the Red Cross (ICRC) and its Central Tracing Agency (CTA) have developed a guidance note on Data and Information Management Regarding Missing Persons [46]. The document establishes guidance on frameworks that national institutions responsible for searching for the missing can follow.

Lastly, an additional potential misuse of these technologies and their reliance on digital data exists. The UN's Working Group on Enforced or Involuntary Disappearances (WGEID) highlighted how new technologies have enabled surveillance and harassment of those investigating or advocating for investigations of cases of disappearance, and artificial intelligence has been used to facilitate multiple human rights violations, including enforced disappearances [94]. Other examples, such as internet shutdowns, the use of biometric data against migrants, or cyberattacks towards NGOs or families of the missing, have become a matter of concern related to the phenomenon of disappearance [94]. As part of this, the WGEID emphasized that technological tools must be implemented within a "human rights framework, ethically and responsibly" ([94], p.14).

[13] Recent documented examples of data breaches, including DNA samples of the missing, have been reported among national institutions and international organizations [59,94].

5. Lessons learned and recommendations

There are multiple challenges linked to disappearance analysis, including the conceptualization and characteristics of the cases, the temporality of the events, the existence of and reliance on traditional strategies to search for people (alive or dead), the capacity for recording events, and the accessibility of software and data required to analyze and preserve information. The existing literature offers valuable insights into best practices, as well as the scope and limitations of using statistical, geospatial, machine learning, and artificial intelligence technologies. In this section, we highlight four main lessons from our review and offer five recommendations based on these findings. Together, they show the development of a novel field of study that promises to be fruitful.

Based on our review of existing methods and experience, four broad lessons can be summarized (L), leading to five recommendations (R).

L.1) DDA techniques are proven to be effective to a specific degree and can complement traditional methods. However, practitioners should acknowledge that some approaches remain experimental and must complement, but never replace, the documentation, fieldwork, and experience of authorities, international organizations, independent forensic teams, and relatives of those who are missing. Furthermore, families of the missing not only provide invaluable information about their loved ones but often participate in searches themselves. Traditional documentation and experiential knowledge are both essential, as these actors are generally skilled at interviewing potential witnesses, making critical observations related to events, and analyzing potential data sources that are often unavailable to analysts. By negating this role and the power of what it produces, DDA's results would likely be very biased and incomplete.

L.2) Researchers must consider potential biases when documenting phenomena associated with violence and severe human rights violations. Although the initial challenges of generating standards for documentation have been addressed [9,12,61,85], stakeholder incentives are likely to continue differing. Some registries and databases may have criminal investigation-oriented objectives, while others may prioritize identifying missing persons, potentially at the expense of the other. There will be instances where these objectives overlap. Methodologies that continue to be developed must consider the context of the social production of this type of information. Above all, results can be reliable only if the original objectives and biases inherent in the data are carefully considered and addressed. For this reason, descriptive statistics must be used cautiously to avoid unsubstantiated claims about the magnitude of the phenomenon, primarily when a single record or database is used [10]. This has even been considered erroneous and discriminatory when documented victims tend to be systematically different from those not documented due to their social visibility [56]. For this reason, record-linkage and statistical inference techniques, such as Multiple Systems Estimations (MSE), have been effective in supplementing these methods, the latter allowing for the comparison of different documentation patterns observed across databases. MSE also gives rise to inferential claims and approximates the absolute number of people who have disappeared in regions or countries under investigation.

L.3) The three types of approximations highlighted in this paper can be complementary and used to understand disappearances more effectively. Databases on missing persons and human rights violations are usually "small" (relative to the overall victim population) and contain many missing values. Recent studies have advanced sample improvement and increased capacities to process larger datasets. For example, the Colombian Truth Commission recently used MSE to estimate the number of people who disappeared during the Colombian conflict [50]. However, the research team faced the challenge of processing multiple databases, pooling the largest number of records in a human rights investigation to date [45]. Given the volume of data and the impracticality of manually classifying cases, record linkage had to be supported

Table 1
Summary of DDA approaches.

Data-based disappearance analysis (DDA) approaches	Summary	Advantages	Disadvantages	Examples of successful implementations
Statistical Inference	Techniques are used to estimate the actual number of victims of disappearances arising from armed conflicts or human rights violations. This approach relies on analyzing the documented patterns of multiple databases or registries with names and other victim characteristics. By identifying the victims documented in various registries and those exclusive to a single registry, statistical inference can be applied to estimate the number of individuals who remain undocumented.	Permits identification of documentation patterns and data quality across multiple registries. Approaches the actual number of victims of disappearances in a country or region. Has been proven effective across various contexts.	Relies on using multiple victim registries, usually no less than three. Has not been used to support the identification of geographic zones in which to search for the disappeared.	The Truth and Reconciliation Commission of Perú and the American Association for the Advancement of Science (AAAS) estimated the magnitude of killings and disappearances in Perú between 1980 and 2000 [11]. The Human Rights Data Analysis Group (HRDAG) estimated how many people disappeared between 17 and 19 May 2019 in Sri Lanka [13]. HRAG and the Colombian Truth Commission estimated the number of killings, disappearances, kidnapings, internal displacements, and forced recruitments in Colombia between the 1980s and 2015 [50].
Geospatial Techniques	These techniques use Geographic Information Science (GIS) software to analyze geospatial data. Combined with layers that represent different types of information, such as terrain characteristics, road networks, or satellite images, descriptive and predictive models can be created to identify locations of disappearances and guide search strategies.	Facilitates the spatial and contextual analysis of disappearances. Does not necessarily require vast amounts of data. Multiple geographic and statistical techniques can be employed.	Acquiring data, such as satellite imagery, and collaborating with judicial authorities can be difficult or expensive. Nonetheless, there are open-source alternatives such as QGIS and Google Earth Pro. Need more practical implementations. To date, mostly theoretical (i.e., models untested).	The Conflict Ecology Lab used satellite images to detect mass graves in Northern Ethiopia during a massacre committed in October 2022. A subsequent on-site inspection of the area confirmed the findings [51]. Researchers from Universidad Iberoamericana, Data Cívica, and Centro de Investigación en Ciencias de Información Geoespacial developed a geospatial model to identify clandestine graves in Baja California, Mexico. The tool assisted a search brigade in April 2023, which yielded two positive findings based on the tool's results [72].
Complex Networks and Machine Learning/Artificial Intelligence	Used to make statistical predictions of the locations of disappearances or the possible status of a person who is either missing or has disappeared. However, they are also being used to help digitize and classify large amounts of documentation related to disappearances. These approaches typically involve larger datasets and greater expertise, using mathematical algorithms to facilitate classification.	Have been applied to cases of missing and disappeared persons. Results can be used in real-time decision-making and "scaled" to be used in different regions or scenarios.	Have had few practical implementations. Risk of mixing or decontextualizing the information used.	Researchers from the University of Buenos Aires, Argentina, and members of the Argentine Forensic Anthropology Team (EAAF) used complex networks to identify potential illegal detention centers where victims of disappearances during the military dictatorship (1974–1981) could be found [23]. The Human Rights Data Analysis Group (HRDAG) and the Colombian Truth Commission utilized machine-learning models to classify and fill in missing data from hundreds of datasets containing information on disappearances in Colombia between the 1980s and 2015 [50].

by machine learning techniques. In other instances, geospatial techniques have been combined with machine learning algorithms to predict or delimit possible search areas for missing persons. In other words, "classic" spatial statistics, such as point pattern analysis or Ripley's K test, were complemented with algorithms such as MAXENT or Random Forest to delimit zones and to be able to scale the predictions to other regions [28,36,77]. These techniques are promising; recent models have successfully helped locate clandestine graves in Mexico [48,72]. However, most of these approaches have yet to be comprehensively validated in the field. Such testing also encourages the development of novel methods to complement existing practices, using data from other tools. For example, forensic teams, academia, civil society organizations, and families with missing relatives are increasingly relying on drones and remote sensing technologies to explore areas in non-intrusive ways [33, 95]. Information collected in this way can also be stored in GIS software for data analysis, complementing previous results.

L.4) Researchers must consider the resource expenditure and accessibility of this type of technology. For example, satellite images are effective across various contexts, particularly when covering temporal aspects or a limited area of interest [43]. However, accessing targeted images can be expensive, especially when higher resolution is needed to identify patterns or disturbances on the ground. In addition, the expertise required to interpret different types of images accurately introduces a resource burden, necessitating the need to train researchers in these methods. Above all, these data forms and technologies must be made available so that local investigators in areas most affected by disappearances can use them, thereby avoiding an unequal distribution of conditions and dependence on outside experts. This effort must consider that most of these studies have been carried out by analysts, organizations, or institutions with significantly more resources, not to mention potentially being based far from underrepresented regions, and with limited availability, subject to unpredictable and shifting priorities.

Given these lessons, we make five recommendations to develop the field of DDA. They complement previous proposals that have focused on creating registries to document disappearances with collaborative schemas and applications of new technologies [18,94], as well as efforts to generate new standards for data protection in the context of human rights, or international criminal investigations [86,89]. These recommendations are not exhaustive and are consistent with the work and literature analyzed above since they consider the context of social production of information about missing people, allow progress in new statistical approaches and machine learning, propose frameworks on the use, preservation, and protection of data, and consider the use of new sources of information.

R.1) Consider existing legal definitions of disappearance types and specific contexts in research.

As argued in Section 2, disappearances are complex since they can represent many different scenarios, including, but not limited to, those related to violence or human rights violations. Analysts must consider independent definitions of these phenomena in developing their models. Databases or records used for DDA often originate from heterogeneous sources with varying standards for documentation and criteria for the inclusion or exclusion of specific cases, which may simultaneously record "missing" and "forcibly disappeared" persons. Analysts must be aware of such semantic issues since these definitions will undoubtedly impact individual models and their results.

R.2) Develop missing persons' data governance schemes and frameworks.

Although "best practices" have been developed for the registration of missing persons, existent proposals must move towards more comprehensive data governance frameworks [47], understood as the "practice of establishing and implementing policies, procedures, and standards for developing, using, and managing the infosphere" ([38], p.3). Data governance is fundamental, imparting individual responsibility to stakeholders regarding the generation, preservation, and security of the data they produce to guarantee the implementation of agreed-upon standards, and to oversee challenges such as privacy, data protection, and the exchange of information between actors [1,3,57]. This is particularly important considering that the regulation of new technologies can lag behind their development and implementation. These schemes must be explored, especially where we are faced with a diversity of stakeholders (i.e., families of disappeared persons, international organizations, government institutions, or NGOs) and their potentially divergent objectives.

R.3) Explore the use of other sources, types of data, and techniques related to disappearances and human rights violations.

DDA has relied on sources that could be considered "traditional", such as records generated by human rights organizations or groups of relatives, and files related to criminal investigations. However, open sources can be explored to complement this information. Open source information "encompasses publicly available information that any member of the public can observe, purchase, or request without requiring special legal status or unauthorized access" ([86], p. 6). For example, families of missing persons have used social platforms, such as Facebook or Twitter, to post photos or share information related to the missing person and potential reasons for their disappearance [81].[14] This information is valuable, as new models must be developed for its analysis, and those models being explored may be able to support the search for missing people while they are still alive. Furthermore, methodologies associated with Open Source Intelligence (OSINT) techniques have demonstrated the potential to retrieve and verify information from these types of sources in contexts of human rights violations or international crimes [21,34,41]. For this reason, the addition of these techniques for data analysis, validation, and systematization should be explored in greater detail.

R.4) Provide broad stakeholder access to data, software, and training, including to grassroots organizations and groups of families with missing relatives.

One major challenge is that organizations and actors collecting and/or analyzing data on missing persons often lack access to the resources required for sophisticated analysis, such as geographic information systems, drones with remote sensors, or satellite images. The provision of these resources and training in their use is important, since much of the data and the results obtained come from local organizations or family groups. International cooperation and funding organizations that support investigations should actively include these stakeholder groups.

R.5) Guarantee that the analysis and results are reproducible, explainable, and ensure a responsible and fair implementation of these technologies.

There is great potential in using new search technologies. However, the acquisition of data and the advancement of techniques and algorithms could also negatively impact victims if they are not used responsibly. It is critical that those who receive and will use the results of analysis (e.g., prosecutors, judges, families) understand it and can seek alternative interpretations or validation. There are serious negative consequences for families and other stakeholders to raised – and sometimes unfounded - expectations with untested methods. For this reason, these initiatives must be reproducible and support implementation, evaluation, and mitigation schemes, as their results could harm already vulnerable populations. Fairness frameworks, which have advanced significantly in statistics and machine learning, must be replicated [16,44,58,87]. More generally, a robust ethics code for the research undertaken must always be in place and implemented.

6. Conclusion

In this paper, we reconstructed and argued for the development of a relatively new area of applied research, which uses statistical inference, geospatial sciences, machine learning, and artificial intelligence methods to support the search for disappeared persons. We labeled this group of technologies, techniques, and methodologies "data-based disappearance analysis" (DDA). The literature review defines the application of DDA in different scenarios, including its promises and limitations.

We highlighted four key lessons and provided five recommendations regarding the definitions of disappearances, the governance of information related to disappeared persons, the potential of new information sources, the importance of ensuring access to tools for various users, and the responsible application of these technologies. A practical and disciplinary effort towards addressing the identified challenges will enable local and international human rights organizations, activists, government, and academia to continue developing a field that generates new methodologies and approaches, strengthening the search for disappeared persons across different scenarios.

CRediT authorship contribution statement

Derek Congram: Writing – original draft, Formal analysis, Conceptualization. **Jorge Ruiz Reyes:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Luciano Floridi:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Sirbu Renée:** Writing – review & editing, Writing – original draft, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

[14] This could bring challenges, such as verifying accounts that use false or misleading information with profiles of missing persons from social media [79].

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