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A multidisciplinary approach to locating clandestine gravesites in cold cases: Combining geographic profiling, LiDAR, and near surface geophysics

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ABSTRACT

By nature, clandestine burials are difficult to locate, an issue that can complicate the legal process, and interrupt the natural grief process of the family. The purpose of this paper is to present a three-step process to search for clandestine graves using (1) geographic profiling, (2) light detection and ranging (LiDAR), and (3) near surface geophysics. Each process incrementally decreases the geographic area being searched, while increasing the level of detail provided to investigators. Using two well-known Australian cases and one experimental study, this paper will demonstrate how (1) can highlight potential search areas, (2) can further narrow down the location of potential burial sites within these search areas, and (3) can assist with locating the clandestine grave. Although each technique on its own can successfully locate graves, combining the techniques can provide the most efficient approach to locate those who are missing and buried.

1. Introduction

Locating missing individuals is important to the legal system as well as to the impacted families. In a legal context, if a crime has been committed, it is very difficult to achieve a successful conviction of a perpetrator when no body has been recovered [1,2] due to an increased difficulty in proving the murder beyond reasonable doubt [3]. For the family, although finding closure may never be possible, locating the remains of their loved ones at least confirms their death, allowing families and friends to begin the grief process and move forward [4,5].

In Australia there are currently over 2600 long-term (>3 months) missing individuals [6]. While there are many reasons people go missing, most of which are not suspicious, some of these individuals have been murdered and left in clandestine graves (defined as any hidden and illegal burial containing human remains). Although Australia boasts a high homicide clearance rate (remained steady at 85% since the 1990s [2]), the rest of the cases remain unsolved due to a combination of a lack of physical evidence (including the body itself), lack of witnesses, and minimal community cooperation [2]. In cases where a body has not be found, factors such as the age of the victim(s), body concealment, apparent motive, involvement of the Coroner, the presence of other evidence, and the offender's ability to engage in detection avoidance behaviour all appear to affect their solvability [2,7,8]. The longer a case takes, the more difficult it is to solve as the investigators face unreliable witness memories (due to time passing since the event), potential loss of witnesses, changes to the investigator in charge, loss or destruction of evidence, and time-altered crime scenes [9].

Due to the complexities involved in solving cold case murders where a clandestine burial has been used as a method of body deposition [10], a multi-disciplinary approach to searching for the remains should be taken. As such, the purpose of this paper is to present a multi-factorial approach to searching for clandestine graves, including three techniques that incrementally decrease the search area while simultaneously increasing the detail of the data output. This investigatory method includes the use of geographic profiling to highlight potential search areas, using light detection and ranging (LiDAR) scanning to further narrow down potential burial sites within these search areas, and then utilizing near surface geophysical techniques to ultimately locate the clandestine graves. Although each technique on its own can successfully locate

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clandestine graves (see Refs. [10–13] for geographic profiling [14,15], for LiDAR, and [16–20] for near surface geophysical techniques), the combination of these techniques makes the best use of their relative strengths for locating unmarked graves, especially in cases where the search area is poorly defined. This is because there is an inverse relationship between the geographic breadth and level of detail each technique can achieve. It is important to note that the only definitive way of locating buried human remains is with excavation, which is time and labour intensive. This process can therefore benefit from the proposed three-step method as it can be used to provide an investigative team with the best evidence in order to locate the grave. As there are no documented cases where the three methods have been used together, this paper will highlight each technique's respective benefits using two well-known Australian cases and one experimental study, that will then be brought together in the discussion, providing a roadmap for a multi-technique process.

Until the 1960s, the English Common law rule of "no body, no murder" [8] meant that if investigators could not find the body, no one could be held responsible. This was because the presence of a body is crucial as it confirms important details, such as the fact that someone has indeed died, and can assist greatly with determining the manner of death (natural, accidental, suicide, homicide) as well as the cause of death (i.e., gunshot wound resulting in fatal blood loss), where the incident took place, and can provide evidence as to who committed the crime (i.e., fingerprints, DNA, or fibres linking the perpetrator to the victim/scene) [2,8]. In the United States however, the *People v. Scott* 176 Cal. App. 2d 458 (1960) [21] case found that if there is enough circumstantial evidence to prove that a death has occurred, and who is responsible, a body is not necessary to achieve a successful conviction for murder [22]. Although there is no Australian equivalent in case law, there have been murderers in Australia who were successfully convicted without the presence of a body, due to compelling circumstantial evidence (e.g. Keli Lane). That being said, it is still difficult to secure a conviction without the presence of a body [3], and is therefore important that investigators have access to various methods to aid them in searching.

2. Geographic profiling

2.1. Background

Geographic profiling is a multi-disciplinary investigative tool combining criminology, psychology, geography, mathematics, statistics, and physics, to understand and analyse the spatial patterns of criminal behaviour [23]. It is grounded within environmental criminology, and is founded on theories of crime pattern [24], routine activity [25], and rational choice [26,27].

Criminal behaviour is a multi-step decision-making process, where the offender manages aspects of the environment and geography, target choice, and time of the offence [24]. This underlying rationality influencing the above aspects allows for patterns to emerge [23,28–30]. Crime pattern theory posits that the chosen environment is ideal to the offender based on the physical, spatial, cultural, legal, and psychological characteristics that can aid with target selection [24]. By continuing to engage in criminal activity, it will categorize these cues as 'good' or 'bad', and ultimately cement as the offender's template (i.e. their modus operandi) [24]. This template can then be analysed and identifiable to the offender because human environmental perception has universal properties, meaning that the spatial and temporal distribution of victims and offenders are clustered and patterned [24,28,31].

Routine activity and rational choice theories are often intertwined because, although the offender may want to engage in criminal activity in an area that is comfortable to them (i.e., near their anchor points, such as a residence or workplace – this is known as their activity space), they will also need to avoid detection (i.e., hunting outside of their anchor points) [26,32,33]. Although the routine activities may be more comfortable, it will increase their chances of being apprehended, thus necessitating the rational choice. This dichotomy between routine activities and rational choices has resulted in two main groups of offenders: marauders and commuters/travellers. A marauder is an offender that hunts away from their anchor points but stays within their activity space, whereas a commuter/traveller creates a buffer zone to avoid detection and hunts outside of their activity space [34,35]. There is a third category, not often taught in geographic profiling, called a troller, which is a combination of both a marauder and a commuter, wherein the offender hunts both within and outside of their activity space [23].

By understanding not only the type of offender, but also their typical hunting patterns and victim choices, geographic profiling techniques can be used to identify an offender's anchor points [9,31,36,37]. This can be done using geographic profiling software, such as CrimeStat, Rigel Analyst, and Dragnet (see Refs. [27,38] for an evaluation of each software and their overall accuracies), or with more traditional mathematical methods such as spatial distribution equations and simple heuristics (see Ref. [39] for the mathematics of geographic profiling and [40] for a comparison between software and human-made profiles).

2.2. Application to clandestine grave location

Geographic profiling has been successfully used to locate serial offenders. In fact, the Australian Federal Police (AFP) employs a full-time geographic profiling analyst that provides geographic profiling support to the AFP and other investigatory bodies in Australia [41,42]. Although identifying a serial offender's anchor points is the more traditional application of geographic profiling, the same techniques can be used to narrow down search areas with the ultimate goal of locating clandestine graves (see Berezowski et al. [23] for a full review). When used in this way, case-specific information, the spatial, temporal, environmental, and geographic (STEG) elements of the crime, as well as offender and victim information, are collated and used to map out areas of interest where potential body deposition sites may be located. Individuals, especially offenders, engage with their environment in a patterned manner, even if they are attempting to act randomly. Those patterns can then be used to predict potential body deposition sites, looking at the key variables mentioned above [33,43]. These variables are highlighted in Table 1, including why they are important to the geographic profile. This information is sought out by police officers, geographic profilers, and sometimes forensic psychologists, and/or criminologists. Directly following is an example of a geographic profile (Fig. 1) that was created using the key variables identified in Table 1 for the Mr. Cruel case, a serial sex offender and murderer, active in Melbourne, Australia in the late 1980s and early 1990s (full case details can be found by Mallett [44]). Mr. Cruel has never been apprehended; however, this profile was created to generate leads in a bid to identify him.

Although the information in Table 1 is displayed as separate lines of inquiry, they are not mutually exclusive factors, and often relate to, or depend on, one another. For example, the case-specific information amassed by the police involves many spatial and temporal factors, such as when and where the victim was last seen, and where the victim and offender/s activity spaces overlap. Likewise, the time since the victim(s) disappeared is not only a temporal factor, but will also affect the spatial, environmental, and geographic factors. More specifically, depending on the amount of time that has passed from when the victim disappeared to when the case is being re-examined, points of interest such as anchor points or last seen locations, the potential routes travelled to and from anchor points or potential body deposition sites, and the geomorphology of the search areas may have changed [59]. These changes can further complicate cold case investigations, and thus need to be specifically addressed. To help with this, open-source software such as Google Earth can display maps from previous years using their 'Historical Imagery' service. Likewise, other useful repositories of information include past building and planning records, civic services like water and electricity,

Table 1
Key variables involved in creating a geographic profile for clandestine grave searches.

Intelligence type	Information collected	Importance
Case-specific information	when/where victim(s) was last seen, and the clothing/ personal items they were seen in [45] residences and workplaces of offender and victim(s) locations the offender and victim(s) frequented telephone records and triangulation of telephone connections [46] witness statements types of vehicles that the offender has access to [28,46, 47]	This information can be used to highlight the activity spaces of both the offender and the victim(s), i.e., where they spent most of their time. It can also demonstrate where the offender and victim could've interacted.
Spatial	potential routes taken to and from points of interest [48] distance between anchor points and points of interest physical and mental barriers such as highways and rivers areas nearby that are discrete, yet accessible [49] offender's awareness space (area just outside activity space)	Once the offender's activity space is mapped out, spatial patterns can be highlighted and analysed. By mapping out the distance between anchor points, the potential routes taken to and from points of interest, highlighting physical and mental barriers, and the offender's awareness space, possible body deposition sites can emerge. Areas that are discrete yet accessible may be desirable [46,49], especially if the area is known (and potentially meaningful) to the offender [11]. More specifically, research has shown that body deposition sites are approximately 15 km from an anchor point, but can be further if the offender has a personal relationship with the victim, and will be 2–3 m away from a road [23].
Temporal	time of year, month, week, and day [29] time since the victim(s) disappearance amount of time that the offender spent with the victim (s)	Time is an important aspect because criminal activity may be more feasible at different times. For example, time of the year is particularly important for places that cycle through periods of extreme seasons, namely winter, as using a clandestine grave for body deposition may not be possible as the ground in some places freezes. Based on an offender's work schedule, certain times of the month or week may be more likely due to pay days and days off. For time of day, although depositing a body at night may provide more protection from being witnessed, depositing a body during the day is easier. The time since the victim(s) disappearance is important, especially in cold cases, because the environment will have more time to change. Lastly, the amount of time that the offender spends with the victim(s) is important because spending an increased amount of time with them may mean that there is more time that needs to be accounted for when questioned. That amount of time can dictate how far out from an offender's anchor points the victim could be buried.
Environmental	geomorphological information such as soil colour, soil depressions or mounds, lack of plant growth, or change in the dominant plant species [10,15,50–53]	The act of digging a grave will permanently disturb the soil strata, resulting in soil colour changes and mounds/ depressions [10]. Digging a grave will also disrupt the surrounding plant environments, resulting in a complete lack of plant growth or increased growth, or if enough time has passed, a change in dominant species [53]. These geomorphological changes can indicate potential areas with clandestine graves.
Geographic	natural formations human-made infrastructure [54]	Each of the spatial, temporal, and environmental aspects are influenced by the underlying geography, however, there are also strictly geographic aspects, such as natural formations, that can influence criminal behaviour. There is also human-made infrastructure (often dependant on natural formations) such as walls, buildings, and lighting that can make certain areas attractive to a criminal [54].
Offender profile	offender demographics, employment history, social interests, and personality [47] organised/disorganized offender [55] offender motivations [47] diagnostic evaluations and offender characteristics [55] how the offender identifies with the crime	Understanding the offender, including their motivations, personality, and potential personality or mental health conditions can indicate what type of offender they are and can highlight potential body deposition sites [55]. Understanding whether the offender is organized or disorganized, or if they have any mental health or personality disorders, will be suggestive of the amount of premeditation and thus detection avoidance [7,23]. Contrarily, there could be an element of impulsivity, meaning that the resulting deposition site will be chosen in haste and may therefore lack meaning to the offender.
Victimology	victim demographics financial situation [59] relationship status and family issues [59] Business or personal concerns or pressures, including health and lifestyle choices [59] relationship between victim and offender [47] how offender identifies with the victim	Victim demographics are important, especially for serial offenders, as they often select similar types of victim [56, 57]. The relationship between the victim and offender, and how the offender identifies with the victim, can be telling of potential deposition sites as well. For example, offenders who feel no remorse for their victims may be deposited in places that mirror this, such as a rubbish tip (see the Mr. Cruel case for an example of this [44]), whereas if the offender feels remorseful, the victim may be buried close to or on the property of an anchor

(continued on next page)

Table 1 (*continued*)

Intelligence type	Information collected	Importance
		point (see the Christopher Watts case for an example of this [58])

and important public buildings/landmarks like police and fire stations [59].

As geographic profiling is essentially a compilation of information, especially potentially subjective case-specific information, one must be cautious with what to include. This is especially relevant to cold case investigations, because the reliability of important information such as witness testimonies, or last seen locations, will inevitably be affected by the passage of time [60]. Although there are no hard and fast rules, only information that is reliable, supported by other sources, and non-conflicting, should be included [23]. Geographic profiles should also exclude external influences, such as other expert testimonies or police theories, as this may affect the final product. Ultimately, it is important to note that geographic profiling does not solve crimes, however, it can generate leads that can guide an investigation. This is beneficial for cold cases, because by definition, they are in need of a new lead, or a new piece of information. When specifically applied to cold case clandestine grave location, geographic profiling can provide police with new areas to search, and new avenues to investigate.

3. LiDAR

3.1. Background

LiDAR scanning is a remote sensing technique that measures distances by precisely timing a laser pulse emitted from the sensor to an object or surface, and back to the sensor [61,62]. Often referred to as laser scanners, these sensors can record multiple returns from a laser pulse and capture millions of points per second [63]. This provides a highly detailed and accurate representation of the physical structures within the study area, both on a large scale when looking at geographic landscapes, and on a small scale when looking at minute details such as body injuries (and anything in between). While LiDAR sensors generally record the distance and intensity of every point, they can also be integrated with photo cameras to provide point colourization. The points extracted from laser pulses are collectively called a point cloud, which can be transformed into a fully coloured 3D model with the appropriate software [64,65]. These models can be moved, measured, and manipulated to allow for overall visualization, or specific measurements/analyses [64]. LiDAR can be used aerially (with a drone or other aerial platform), or terrestrially (with a tripod). It can also be attached to a backpack or to a moving vehicle, depending on the required detail of the scene. A review of the use of LiDAR for forensic purposes can be found in Berezowski et al. [66].

Using LiDAR technology, especially in a forensic capacity, is beneficial for three reasons. Firstly, data capture (particularly terrestrial) is relatively easy, and the technique is not time and labour efficient. Relatively large search areas can be covered in a short amount of time [67], with minimal personnel necessary for operation. The length of time for each scan is mainly contingent on the type of the LiDAR system and its settings as well as terrain complexity, however, a single outdoor scan using a terrestrial laser scanner can take as little as 5 min [65]. Generally, the most time-consuming part of using LiDAR technology is the data processing, the length of which depends on available computing resources, software licenses, and user competence [64,66]. Secondly, 3D models allow for easy and accurate point to point measurements [64], facilitating analyses that may not be possible otherwise. Thirdly, and perhaps the most beneficial, is the visually intuitive nature of the end-product. This is especially relevant in a forensic capacity, as expert testimony can be misunderstood by jury members, ultimately affecting

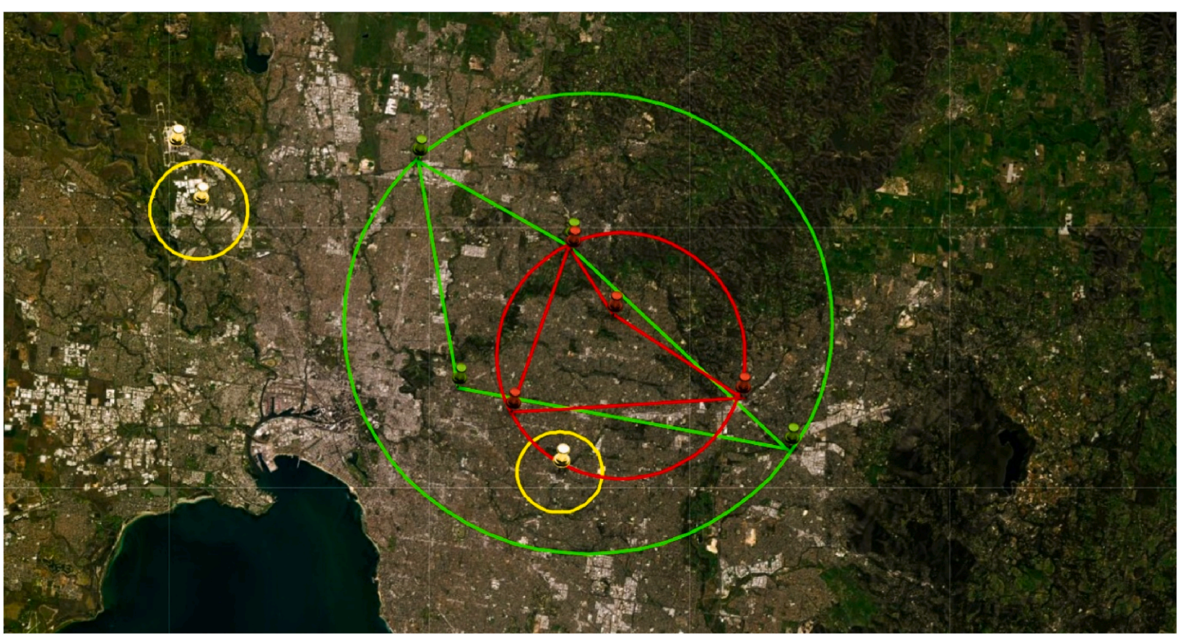

Fig. 1. – Geographic profile of the Mr. Cruel Case in Melbourne, Australia. The red pins represent the abduction/attack sites of his four victims, with the red circle and red polygon highlighting a small portion of Mr Cruel's activity space using the circle theory and convex hull methods respectively.[11] The green pins represent the release/deposition sites, with the green circle and green polygon encompassing Mr Cruel's activity space using the circle theory and convex hull methods, respectively. The yellow pins and circles represent two important areas to the case. The yellow circle and pin inside the large green circle denote a highly likely area for Mr. Cruel to have lived (Burwood), with the yellow pin and circle in the top left which includes five neighbourhoods that Mr. Cruel may have taken two of his victims to, as it is close to the Melbourne airport (yellow pin in top left), and two victims recounted hearing planes overhead in their witness accounts [44]. This profile would benefit the police investigation, as it demonstrates the most likely areas to search (the red and green convex hulls), which could generate new leads and potentially apprehend the person responsible. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

their ability to make an informed judgement [68]. A 3D model can allow for better understanding of expert testimony [69,70], and can provide jury members with a feeling of navigating through the scene, which is not possible in 2D images or plan drawing sketches [66].

There are also drawbacks to using LiDAR technology; namely the cost, need for training, inability to capture certain scenes/surfaces, and the time intensive nature of data processing. Firstly, laser scanners are expensive, which may deter agencies or practitioners from using these devices. As for training, although laser scanners allow for accurate scene reproduction, there is a need for extensive training, both in operating the machine and during data processing, though this limitation can be mitigated by outsourcing to a third party. Next, there are certain surfaces and scenes that LiDAR technology may have difficulty scanning, including objects beyond the effective range of the scanner and reflective/transparent surfaces [66].

Finally, the use of LiDAR scans involves data processing techniques that can be time consuming, even for experienced practitioners. Data processing generally involves four main steps, including point cloud registration, filtering, classification, and finally undertaking the desired analysis. Point cloud registration involves automatically (done by computer software) or manually (done by the operator within computer software) aligning multiple scans together (e.g. bringing them into the same coordinate system), to reflect an accurate reconstruction of the scene [65]. There are two main ways to accomplish this, including target-based and targetless registration (for full explanation, see Berezowski et al. [66]). Point cloud filtering is not always necessary; however, LiDAR capture often results in extra data that may not be necessary to the scene reconstruction and subsequent analysis. There is also the chance that there will be a problem with registration resulting in noise or features that are wrongfully reconstructed. In both cases, the extra data should be removed prior to any analyses. Often point cloud classification is required to differentiate between points belonging to bare ground and other objects (for example trees, shrubs, and buildings etc.), and is generally performed automatically using morphological filter-based algorithms. The final step will be contingent on the purpose of the LiDAR scan, which in this context can include elevation measurements (elaborated on in section 3.2) [14,15,71–73].

3.2. Application to clandestine grave location

A review of the literature on LiDAR technologies used to search vast landscapes ranges from archaeological uses (see Chase et al. [14] for a comprehensive discussion on its archaeological applications), to topographical surveys from space [74]. Very little of the available literature pertains to its application to forensically significant burial searches, with the exception of Corcoran et al. [15] and Ruffell et al. [75]. In fact, most of the literature on LiDAR in a forensic capacity focuses on the capture and analysis of smaller scale evidence (when compared to large scene capture), such as human remains [65] or deceased individuals at autopsy [76–78], as well as to aid with crime scene reconstruction [64] and crime scene analyses such as blood stain pattern analysis [79–81], bullet trajectories [63,82,83] and footwear impression analyses [84]. As the second step in the presented multidisciplinary approach to cold case clandestine grave location, LiDAR technology, either aerially or terrestrially, can further narrow down the search areas identified in the geographic profile. Although LiDAR cannot directly detect bodies in the subsurface, applying it in such a way has three main benefits: 1) the ability to cover large areas in a short amount of time, 2) the capacity to penetrate tree canopies, and 3) the capability to detect subtle elevation changes associated with clandestine graves.

Without the application of digital methods, searching multiple and potentially expansive areas can be time and labour intensive [85]. In these situations it can be useful to engage forensic anthropologists or forensic botanists to systematically search the area and look for surface irregularities (see 'Environmental' section of Table 1) [86]. Applying LiDAR, especially aerial-based LiDAR, can be helpful in surveying large areas in a short amount of time (when compared to the time it would take to complete a foot search) [67,87], while still producing a high-quality and accurate reconstruction of the scene that can enhance its interpretation [14].

An additional benefit is LiDAR's ability to penetrate tree cover [14,67,88,89]. From an offender's perspective, forested areas are an ideal location for a body deposition site as they help to conceal the perpetrator while emplacing the body and making grave location more difficult. Aerial LiDAR can quickly survey large, forested areas, penetrating through the tree cover (shown in Fig. 2), which can then be further analysed for potential gravesites, as well as the identification of access and egress routes. Some of the laser pulse energy is reflected back by the tree canopy, however the rest will penetrate through, capturing the branches and the ground [89]. Glennie et al. [67] highlight this, demonstrating that geometric patterns and landscape modifications that were clearly human-made were visible through the tree canopy. Although graves are considerably smaller than many archaeological features, the visible surface disturbances associated with digging a grave may be detectable with aerial LiDAR. Doneus and Briese [89] caution users however, stating that although many commercial aerial LiDAR systems can distinguish between the trees and the ground, smaller vegetation such as ferns and bushes may be more difficult to visualize, thus making elevation changes consistent with graves difficult to identify. Prior to undertaking a full LiDAR survey over a forested area, Crow et al. [88] discuss the importance of vegetation awareness, as certain species may be more difficult to penetrate. The authors also discuss the benefits of conducting a visual vegetation mapping assessment, which can provide LiDAR penetration estimates that can predict the effectiveness of the survey in mapping sub-canopy features [88].

Finally, LiDAR can detect subtle elevation changes [14,15,71–73] that often accompany the creation of clandestine graves, even years or decades later. This is useful because these changes, which are created by the displacement of soil resulting in an initial mound but with time resulting in a depression due to settling soil, are often invisible to the naked eye [87]. There are various ways to analyse the data for elevation changes, including hill-shading [93], principle component analysis hill shading [94,95], the sky-view factor [96], slope analysis [97], local relief modelling [98], geomorphons [99], models of solar insolation [95], and colour shading [95],[2]. Essentially, each technique highlights the areas with an elevation change with metre and sub-metre resolution (see Fig. 3) [14,73,75,85,100,101]; even small height differences that may have no surface expression. Bewley et al. [100] note that LiDAR's ability to identify small height changes is done at a resolution and accuracy that historically, has only been achieved with labour intensive fieldwork. In fact, modern high-end terrestrial laser scanners can measure up to 1.2 million points per second with an accuracy of 5 mm [102], and modern high-end aerial laser scanners can measure up to 1.5 million points per second with an accuracy of 10 mm [103], which cannot be achieved using other survey techniques. It is important to note that although the above noted articles have archaeological applications, they can be applied to a forensic setting because the elevation changes

[1] The red and green circles in Fig. 1 are derived from Canter and Larkin's [35] original geography-of-crime theory, which posits that if a circle is drawn around the two furthest sites of interest, the offenders anchor point is likely inside the circle. Due to the vast amount of space to search within the circle, the convex hull method was created as the more modern and accurate update. More specifically, the convex hull can be any shape, that is created by connecting each of the sites of interest into a polygon. The convex hull is within the circle and denotes a smaller search area.

[2] Although an in-depth discussion of each type of analysis is out of the scope of this paper, both Chase et al. [31] and Challis et al. [99] provide clear discussions on their uses and benefits to elevation analysis.

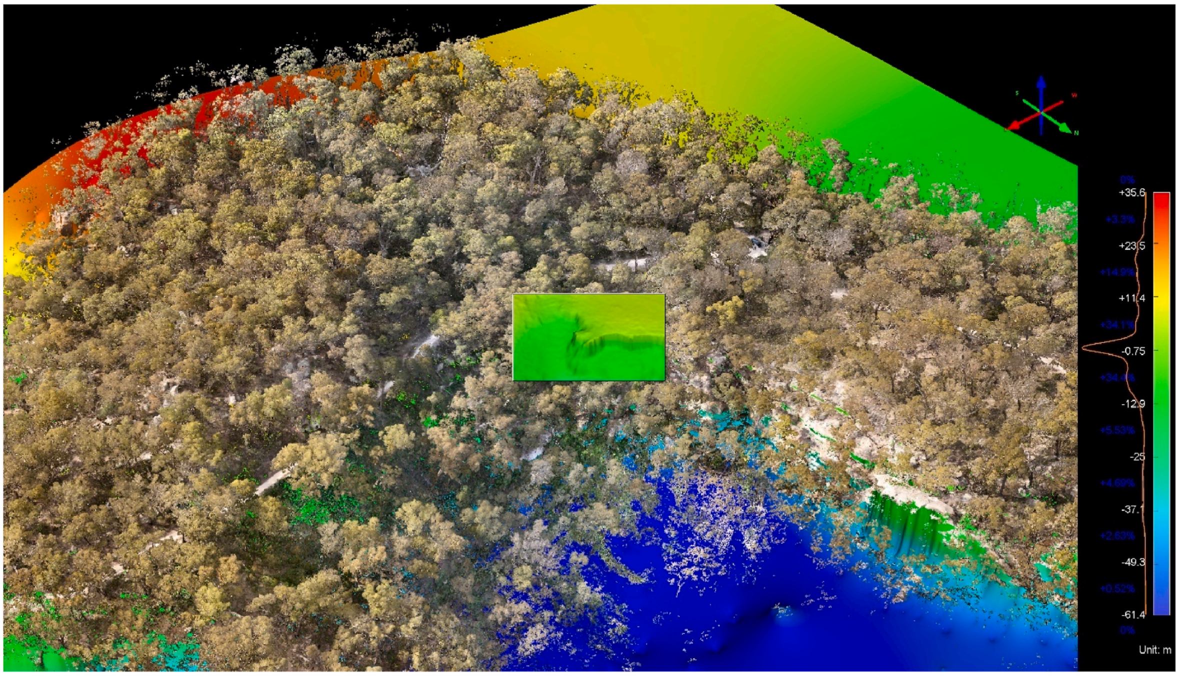

Fig. 2. – Done-based LiDAR capture over large, forested search areas. 3D model, captured with drone-based LiDAR, of the Belanglo State Forest in New South Wales, Australia. This type of LiDAR capture allows for an overall scene view, as well as the ability to see through the tree cover. The colour bar on the right highlights the relative heights of the surface (height above drone launch point), showing elevation changes. This is helpful when search areas are in forests, such as the case for Australian serial killer Ivan Milat. This is the site where Milat deposited his seven known murder victims. A full case summary can be found at [90]. This figure was captured using Emesent Hovermap [91] and visualized in Quick Terrain Modeler [92]. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Fig. 3. – Terrestrial LiDAR capture through large, forested search areas. 3D model, captured with terrestrial LiDAR (attached to backpack), of the Belanglo State Forest in New South Wales, Australia. With similar benefits to drone-based LiDAR, this method allows for a detailed view through dense forested areas, including the potential to see mounds or depressions in the soil that could be possible clandestine graves [15]. This figure was captured using Emesent Hovermap [91]and visualized in CloudCompare [104].

present similarly and can thus be identified using LiDAR data. This was highlighted by Corcoran et al. [15], who utilized terrestrial LiDAR to characterize the elevation changes from simulated burials. The authors noted that there were observable elevation changes where the graves had been dug, and as well as a lack of undisturbed areas [15]. Although their elevation analyses only spanned four months, Keatley et al. [10] note that in clandestine grave situations, it is rare that the soil and surrounding areas return to 'normal', therefore indicating that these elevation changes can be seen years later. The authors also noted that although there were areas that show an elevation change, often associated with natural processes, they were not the same as the localized elevation changes consistent with grave disturbances [15].

Whether used aerially or terrestrially, LiDAR data capture for the purposes of clandestine grave location needs to be systematic and executed in a manner that extracts all possible information from the search area. An operator must be selective about which area they wish to cover, and how dense the resulting point cloud will be [105]. A less dense point cloud will save on scanning time, however it will result in a reduction in resolution [105]. Similarly, the accuracy and precision of the LiDAR system should be taken into account, as a LiDAR sensor able to produce high point densities but with relatively low accuracy (>25 mm) may lead to inaccurate measurements [106] in areas with small elevation changes. To ensure that an entire scene/area is captured, multiple scans should be taken. The key to accurately registering these scans together at the data processing stage lies in having enough overlap between each scan, meaning that the LiDAR placement (or flight plan if aerial) is crucial and needs to be well thought out prior to survey [65].

4. Near surface geophysics

4.1. Background

By measuring various physical properties such as dielectric permittivity, electrical resistivity, acoustic velocity, magnetic intensity, or gravity, geophysical techniques are able to examine the subsurface [107]. Their success relies on the equipment's ability to measure the appropriate physical properties that are impacted by the target of the investigation, which in this context is a clandestine grave [108]. There are various types of geophysical techniques capable of locating clandestine graves, with popular ones including ground penetrating radar (GPR), resistivity, including fixed probe resistivity (FPR) and electrical resistivity tomography (ERT), as well as magnetometry and gravity. This paper has a focus on GPR and resistivity methods, as they are the two most common, however, a brief overview of the latter two, and their application to clandestine grave searches, can be found in Moffat [109]. In this section, as FPR and ERT are founded in the same scientific principles, they will be referred to as resistivity methods when referenced collectively, and then by their individual abbreviations when referenced separately. Although this manuscript only includes a brief overview of both radar and resistivity methods, a full review can be found by Berezowski et al. [110].

4.1.1. GPR

GPR emits electromagnetic (EM) waves into the ground, that are reflected back as they reach subsurface features with varying dielectric properties [46,109,111–113]. These reflections are recorded as one-dimensional (1D) traces, which are then automatically combined and visualized as a 2D profile on the GPR display. The output data can then be transformed into a 3D cube for further visualization and in-depth analyses [109,114,115]. Dielectric permittivity (defined as the polarisation that a material experiences when affected by an external electric field) is controlled by composition, water content, and porosity [111,113,116,117]. A higher amplitude response will be received when there is greater contrast between the dielectric permittivities of adjacent subsurface materials [110]. This, coupled with a depth analysis (measured by the EM wave return time and the estimation of velocity properties [109,114]), provides detailed information about the subsurface.

Numerous factors such as antennae frequency, trace increment, and line spacing should be considered when performing a GPR survey. Antennae frequencies can range from 50 MHz to 2000 MHz [118–120] and will affect the depth penetration as well as the vertical resolution [115,121]. Lower frequencies allow for more depth penetration, whereas higher frequencies have higher resolutions [114]. This has been made easier with multi-frequency antennae, allowing for greater depth penetration as well as high resolution data [111]. Most forensic searches utilize frequencies ranging between 250 MHz and 900 MHz [122,123]. As for trace increment and line spacing, a shorter interval and spacing respectively, will increase data resolution but will also increase survey time [113]. To ensure the target is found, the line spacing should be no more than half of the shortest possible axis of the feature being detected [110]. When searching for an adult grave, a line space ranging from 0.2 m to 0.5 m should be utilized.

Once the data has been collected, it can be processed and interpreted. Common data processing techniques include filtering (removing very high or very low frequencies, removing noise), gain correction (increasing visibility by making deeper parts more visible), and migrating (removing point source hyperbolas to their sources and correcting orientation for dipping layers) [111]. An additional processing step includes combining 2D profiles into 3D cubes, which combines all amplitude values that can be displayed in any orientation [17]. 3D cubes are advantageous when the subsurface materials are complicated and difficult to resolve [124]. Once the data is sufficiently processed into an interpretable format, it can then be assessed for any features consistent with the target of the investigation (see Conyers [125] for an in-depth discussion on GPR interpretation). The main issue is that not all subsurface anomalies will be relevant to the target search. For example, when attempting to identify a clandestine grave, additional subsurface anomalies such as tree roots, drastic lithology/soil changes, or voids associated with animal or non-suspicious human activity may resemble an anomaly associated with the grave. To ensure an effective interpretation, an accurate hypothetical model and a comprehensive history of the site (both geologically and historically) must be considered together, focusing on the dimensions of the target, the characteristics of the soil (including the porosity, lithology, water saturation, and chemistry), and the characteristics of the target (including the state of decomposition and the presence of other materials) [110]. 3D modelling of GPR data can also be beneficial, as shown by Kelly and et al. [126], who found that certain subsurface features relevant to the search were only detectable on the 3D model.

4.1.2. Resistivity

Resistivity methods, such as FPR and ERT, require at least four metal stakes (known as electrodes) to be inserted into the ground, that measure the electrical resistance of the subsurface between two current (injects current) and two potential (measures potential) electrodes [127]. Resistivity is controlled by the composition, porosity, fluid saturation, and chemistry of the subsurface materials [127]. A grave may exhibit a higher or lower resistivity value than the surrounding soil [109]. An FPR survey uses electrodes at a fixed spacing that move systematically around the site at a fixed distance from each other, producing a 1D plan view of the subsurface [128]. In contrast, an ERT line consists of multiple electrodes, placed equidistant and in a straight line, from which many different measurements between four electrodes are combined to create a 2D profile [128].

Factors such as line length, electrode spacing, and electrode configuration will control the depth and resolution of the resulting data. Firstly, the maximum depth of the survey is contingent on the total length of the ERT line, with the electrode spacing controlling the resolution, resulting in penetration that is approximately 20% of the total line length [109,129]. Additionally, there is an inverse relationship between electrode spacing and the resulting resolution, as an increase in spacing results in a decrease in resolution. Finally, electrode configuration can affect data resolution and sensitivity, and sign ratio [128].

Much like GPR, resistivity data needs to be processed and interpreted. For data processing, the main difference between FPR and ERT is the need for the latter to be inverted [127]. An inversion mathematically models a depth section of estimated resistivity based on the surface measurements of apparent resistance (detailed discussion on apparent resistance in Schmidt [127]), and is usually done by a least-squares optimization method [110,130]. FPR data processing usually consists of data improvement (cleaning up data defects), data processing (further highlighting important anomalies), and image processing (proper data presentation for better understanding) [127]. In addition to this, a synthetic model, presenting how the target will affect the subsurface resistivity, can enhance the interpretation of both FPR and ERT data [110].

4.2. Application to clandestine grave location

As the final step in the proposed search method, near surface geophysical techniques can survey the areas highlighted in the first two steps, hopefully locating the clandestine grave. Although some geophysical techniques (namely GPR) can survey larger areas in a short amount of time, their application to clandestine grave searches is benefited by first using geographic profiling and LiDAR capture. Although measuring different physical properties, radar and resistivity methods are able to detect burials because of the difference between natural/background soil and disturbed soil [131], however, the location of voids, material items (such as clothing, wrapping, or weapons), and (very rarely) skeletal material can also be detected [116,121,132,133]. One of the main benefits of using radar and resistivity methods, is that they are non-invasive, and don't affect the integrity of the buried evidence [15,116].

GPR can survey large areas in a short amount of time at the highest resolution (compared to other geophysical methods), making it the most commonly used technique for grave detection [51,116,134]. Fortunately, where GPR falls short, resistivity may be a viable alternative. However, data collection is much more time intensive, being approximately 100 times slower for a single line with 25 times less horizontal resolution [110]. The ideal and non-ideal areas in which both GPR and resistivity methods operate are shown in Table 2.

One of the benefits of utilizing near surface geophysical techniques to locate clandestine burials is that the time since burial is less of a factor in its detectability. This is because the techniques usually detect the soil disturbances associated with the grave [122,140], and not the grave itself (see Damiata et al. [133] for an example of direct detection of skeletal remains by GPR). Although there may be more of a surface disturbance with recent burials, the subsurface changes take a considerable period to return to a pre-burial state [10]. Dick et al. [141] provide a useful graphic demonstrating the effectiveness (good, medium, and poor) of various geophysical techniques in detecting graves at varying ages (ranging from 0 to 100+ years). The authors found that GPR was a mix between good and medium for all burial ages (including a category they specifically named clandestine grave), and resistivity was good for graves aged 0–50 years as well as clandestine graves, medium for graves aged 50–100, and poor for burials aged 100+ [141].

Table 2
List of ideal and non-ideal search areas for radar and resistivity methods.

Search Area	GPR [a]	Resistivity [b]
Ideal	Flat Dry, sandy [115] Clear surface/subsurface Freshwater [135,136]	Hills/uneven High saline, clay rich Surface/subsurface with extraneous objects such as gravestones or rocks; tall/dense vegetation Salt water [136,137]
Non-ideal	High saline, clay rich [115] Surface/subsurface with extraneous objects such as gravestones or rocks; tall/dense vegetation	Dry, lacking moisture Uneven terrain [c]

[a] – information sourced from Schultz [116] unless otherwise specified.
[b] – information sourced from Moffat [109] and Pringle et al. [51] unless otherwise specified.
[c] – resistivity methods can easily acquire data on uneven terrain, however, the trenching effect (defined as the unknown difference in electrical properties of disturbed versus undisturbed soil [138]) needs to be considered, as graves in these conditions can produce misleading anomalies [138,139].

When interpreting subsurface anomalies, it is important to know the approximate size and shape of the burial, as well as the depth and the presence of other items with the burial. The former two may seem obvious, however, they are important as they can differentiate between non-grave anomalies. For example, an average adult burial will measure approximately 1 m by 2 m (based on the average size of an adult human being), therefore, if the anomaly being detected is much smaller, or much larger than that, it can be excluded as a grave of interest to excavate. The average depth of a forensically significant grave is 0.5 m, and rarely more than 1 m [124], therefore if the detected anomaly is significantly shallower or deeper than that, it can be excluded. Finally, target composition can be helpful when interpreting the detected anomalies, because certain material objects can provide strong responses, such as weapons, or metal personal items [140,142]. Likewise, if the individual is wrapped, in tarpaulin for example, the anomaly may be different than the surrounding soil, thus detectable by GPR and resistivity methods [124,143–145].

5. Discussion

Due to the time and labour-intensive nature of excavation, utilizing a multi-disciplinary approach to locate remains, such as the one presented here, should be employed. This search technique, when used in the order presented, can incrementally decrease the geographic area needing to be searched, while increasing the level of detail necessary to locate clandestine graves. Although no single case has been published where these three techniques have been used together, the following section will discuss the merits of each technique separately (making reference to two well known Australian cases and one experimental study) and conclude with a forensic case wherein a similar multidisciplinary method was used, and a potential case where the presented method would be beneficial.

Firstly, Fig. 1 shows a geographic profile of Mr Cruel's criminal activity, the Melbourne serial child sexual assault offender and potential murderer. Although never officially applied to the case by the investigating bodies, this profile has narrowed down the potential areas that Mr Cruel may have lived, worked, or had significant ties to. These are shown by the yellow pins and accompanying yellow circles. In the 1990s, the police searched over 30,000 homes across 15 neighbourhoods without success. These neighbourhoods were selected due to their proximity to the airport, as two of the victims could hear loud airplanes overhead [44]. Although this was an important line of enquiry, these neighbourhoods were well out of Mr Cruel's known activity space (shown as the green circle in Fig. 1). Based on geographic profiling principles, Mr Cruel likely had an anchor point within this space. Unfortunately, this area is approximately 616 square kilometres (the green circle has a 28 km diameter), which would not have been feasible for a search. Instead, the overlap of the red and green circles (circle theory), as well as the red and green convex hulls (updated circle theory) show a more condensed area where Mr Cruel may have been found. In fact, the results of this geographic profile demonstrate that Mr Cruel likely had an anchor point in Burwood. Without new evidence, it is improbable that this case will be re-evaluated by Victoria Police, however, this geographic profile shows a much more detailed and accurate approach to how the police could have applied their resources.

Next, once the geographic profile has narrowed down potential search areas, LiDAR technology can be used to further investigate each of the selected areas. This is exemplified by the geographic profile of Ivan Milat generated by Berezowski et al. [23], in conjunction with Figs. 2 and 3 above (screenshots of 3D models from Belanglo State Forest). As a brief introduction, Ivan Milat was convicted of abducting and murdering seven backpackers in the Belanglo State Forest (see Mallett [90] for full details). Berezowski and colleagues [23] created a map displaying the priority search areas in Belanglo State Forest to locate additional victims (if another search was allowed by police) – this can be seen in Fig. 6. Completing a LiDAR survey of these areas can be done relatively quickly, when compared to the speed of traditional mapping techniques. The resulting data can then undergo elevation analyses (as shown above) that could highlight potential burial sites by locating subtle topographic anomalies with appropriate dimensions that could be a grave.

As the final step, geophysical techniques can survey those areas exhibiting elevation changes consistent with a clandestine grave, to further narrow down the presence of a grave prior to excavation. This is an important step because Corcoran et al. [15] demonstrate that not all elevation changes will be from a grave, and thus need to be further

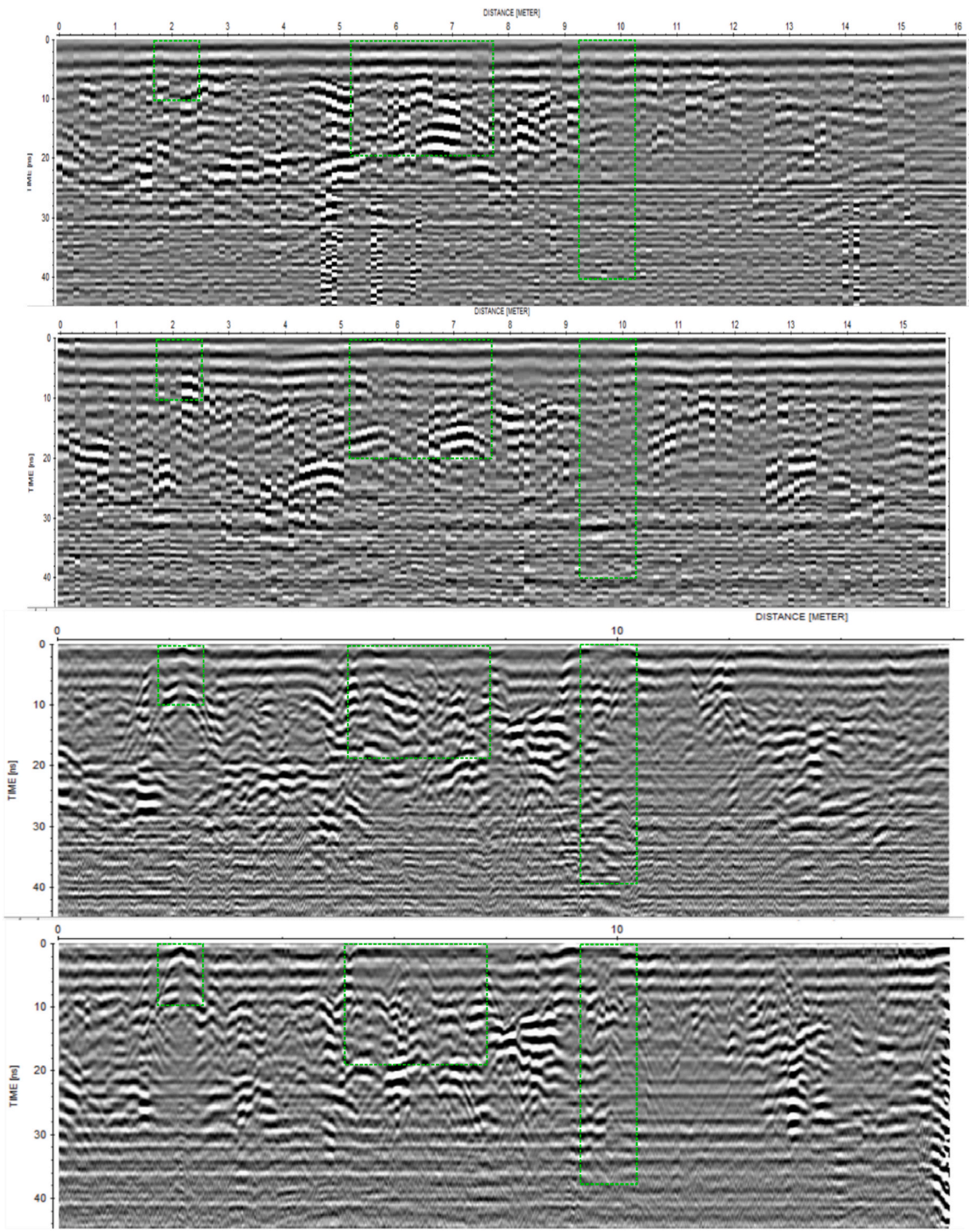

Fig. 4. – GPR profiles of pig cadavers simulating human burials over a six-month timeframe. Three simulated pig burials were created at the Australian Facility for Taphonomic Experimental Research (AFTER) and surveyed with GPR pre-burial, and then one-day, one-month, and six months post burial (in this order from top to bottom). The grave locations are shown by the green rectangles, with the left grave being a single burial (one pig) at a depth of 0.5 m, the middle grave being a mass grave (three pigs) at a depth of 1 m, and the right grave being a single burial (one pig) at a depth of 2 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

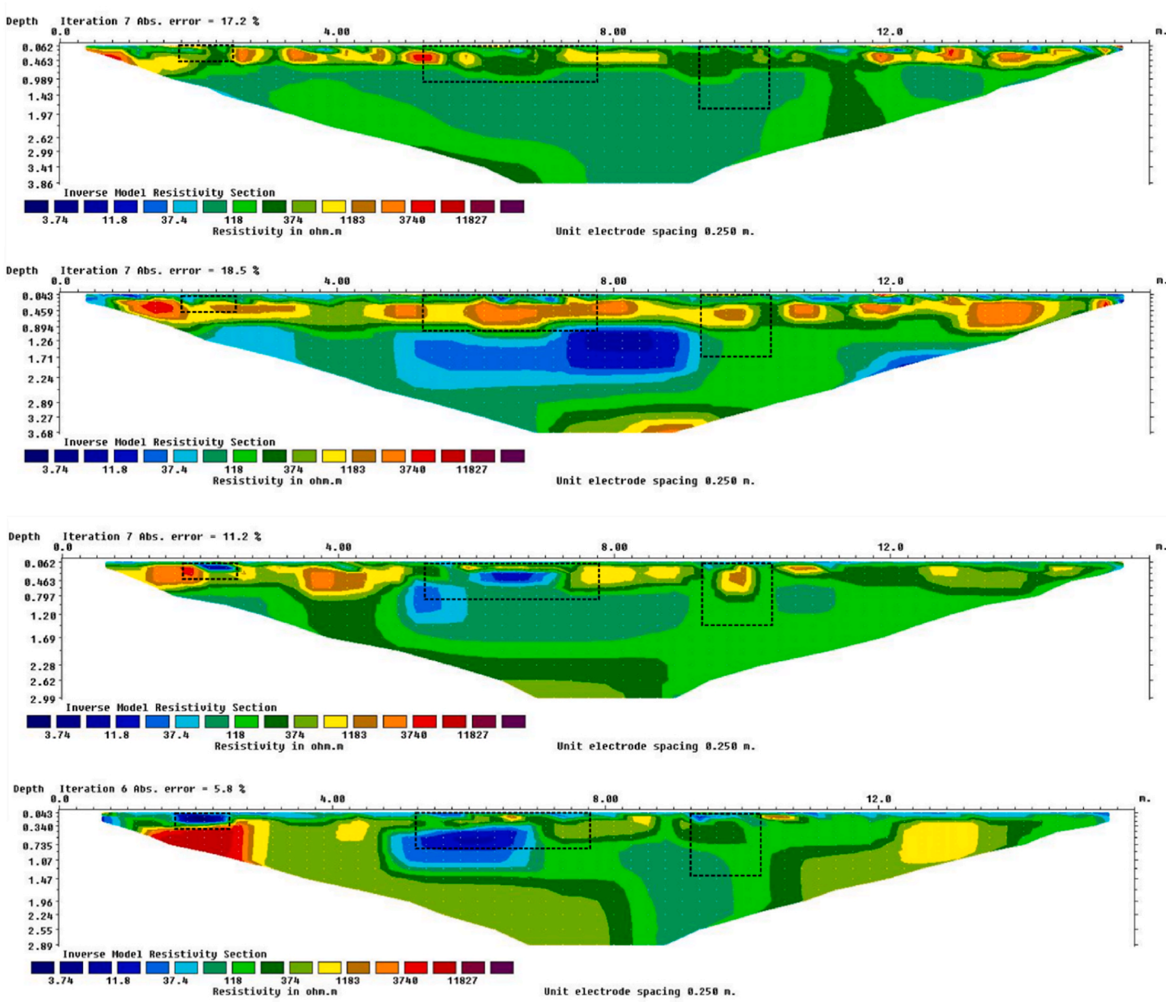

Fig. 5. – ERT profiles of pig cadavers simulating human burials over a six-month timeframe. ERT surveys were also done over the pig burials at AFTER, pre-burial, and then one-day, one-month, and six-months post burial (in this order from top to bottom). The burials are shown here by black rectangles (see Fig. 4 description for type and depth of burial).

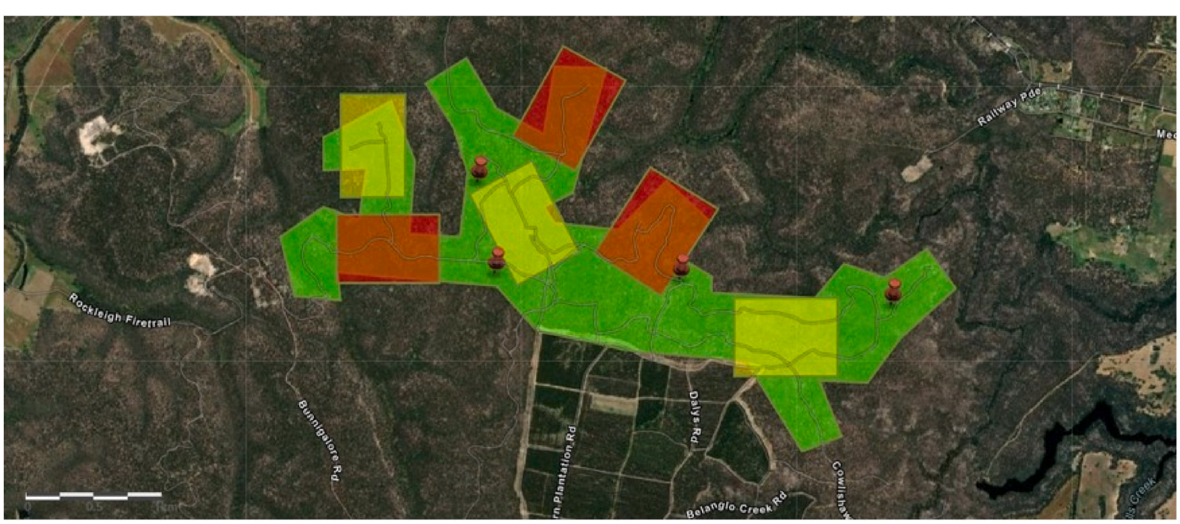

Fig. 6. – Prioritized search area for additional Milat victims in Belanglo State Forest. Originally presented in Berezowski et al. [23]. The green area denotes 150 m off both sides of the fire trail, highlighting the ideal search area (with no money or time constraints). As a search this size would likely be too time consuming and expensive, the red and yellow rectangles demonstrate the primary (red) and secondary (yellow) priority search areas for additional Milat victims. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

investigated with other methods. Both Corcoran et al. [15] and Aziz et al. [72] highlight that geophysical techniques should be used after LiDAR data has narrowed down potential gravesites, favouring a multi-disciplinary method. If an anomaly consistent with a grave is seen in the geophysical data, the site can then be marked for excavation.

The results of these surveys shown in Fig. 4 illustrates the complexities of locating unmarked graves using GPR. The most obvious grave related anomaly is the hyperbola in the left graves where the GPR is detecting the pig cadaver itself. The remaining two graves, however, are more subtle. Hyperbola are present from the pigs in most cases, but they are difficult to distinguish from hyperbola associated with other subsurface features. The most reliable indicator of graves in these profiles is disturbances in the otherwise relatively continuous horizontal near-surface reflectors present through most of the rest of the profile, reflecting the disturbance to the soil stratigraphy caused by burying the pigs. This correlates well with previous studies on the efficacy of GPR for grave detection, which usually consider the reliable direct detection of graves difficult under field conditions [146].

The indications of graves in the ERT data shown above in Fig. 5 are also complex. The most obvious grave related anomalies are the conductive (dark blue) responses associated with the middle grave. While there is a good association between this feature and the buried pigs, the shape of this feature does not correspond well to the known dimensions of the grave, suggesting that it is related to fluid leaking from the pigs. The left grave also has a conductive response, although this corresponds better in geometry to the known dimensions of the grave, perhaps because there is less fluid escaping from this single pig. The right grave has a very subtle geophysical response, defined by a slightly resistive anomaly above the cadaver which probably represents additional soil porosity in the grave fill.

The most important lesson from the geophysical data presented in Figs. 4 and 5 is that the geophysical responses of these burials are subtle, and they may not have been identified as burials without the pig locations being known. This is likely due to the undeveloped nature of the soil at the research facility. The disadvantage of subtle responses is that they may not be prioritized for excavation, which in this context, would result in not successfully locating the grave and not being able to solve the case.

In order for these methods to be used most effectively, case-specific information such as the residences, workplaces, or frequently visited areas of the offender and victim(s), telephone records, and witness statements are crucial in creating an accurate geographic profile. Other important lines of inquiry include comprehensive searches of site histories, including past commercial or residential uses, soil characteristics, and climate patterns. Background information is also critical to accurately locating burials in LiDAR and geophysical surveys [101].

The combined use of these three techniques would not be beneficial for every case. For example, geographic profiling can only be used on serial offence cases, or in cases with multiple relevant locations (i.e., missing persons or body deposition site location cases). Additionally, LiDAR and near surface geophysical techniques will not operate optimally in all environments, including areas of complex topography, and areas with uneven terrain or where surface obstructions exist (see Table 2), respectively. Despite these limitations, under favourable scene conditions, the combined use of geographic profiling, LiDAR, and near surface geophysical techniques can prove optimal in cold cases where a clandestine grave must be located.

An example of a recent forensic case where a similar multi-disciplinary method for locating the grave of a missing person was used successfully, was by Molina et al. [19] who used a combination of police intelligence, geographic profiling, and a geophysical technique (ERT) to narrow down and survey two sites of interest. Finally, an example of a case where the three techniques would be effective when used together is that of Ivan Milat. Although he died serving seven life sentences, it is hypothesized that the seven people he was convicted of killing were not his only victims (see Berezowski et al. [23]). Based on his previous body deposition site choices (i.e., forested areas), the three techniques presented here could be used to locate additional victims. More specifically, the prioritized search area presented in Fig. 6 (narrowed down using geographic profiling) can be searched with LiDAR to highlight potential graves via elevation analysis. The resulting anomalies most consistent with covert burials could be investigated with near surface geophysics.

6. Conclusion

In conclusion, the purpose of this paper was to present a three-step process to search for clandestine graves that incrementally decreases the geographic area being searched, while increasing the level of detail provided to investigators: beginning with 1) geographic profiling, followed by 2) LiDAR], and finally 3) near surface geophysics. Although there has been no published case where the three presented techniques have been used together, this paper demonstrated the benefits of each method when applied to clandestine grave location, with the aim of promoting the effectiveness of their combined application. Ultimately, the use of this three-step method can increase the likelihood of finding those who have been murdered and covertly buried, allowing for a greater potential for identifying and prosecuting the person(s) responsible, and a final return to their loved ones.

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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.

Author contributions

Victoria Berezowski: Conceptualization; Methodology; Investigation; Writing – Original Draft; Visualization; Funding Acquisition Ian Moffat: Methodology; Resources; Writing – Review & Editing; Supervision Yuri Shendryk: Methodology; Resources; Writing – Review & Editing Douglas MacGregor: Methodology; Resources; Writing – Review & Editing Justin Ellis: Writing – Review & Editing; Supervision Xanthé Mallett: Conceptualization; Methodology; Resources; Writing – Review & Editing; Supervision.

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