Received: 17 June 2024 | Revised: 4 November 2024 | Accepted: 6 November 2024

DOI: 10.1111/ejss.70019

RESEARCH ARTICLE

European Journal of Soil Science WILEY

Integrated, multiscale forensic soil science applied to an unsolved murder case in Italy

F. Terribile[1,2] | M. Iamarino[2] | G. Langella[1,2] | Giacomo Mele[3] | L. Gargiulo[3] | F. A. Mileti[2] | S. Vingiani[1,2] | L. Dawson[4]

[1]Dipartimento di Agraria, Università di Napoli Federico II, Portici, Italy

[2]CRISP Research Centre, Università di Napoli Federico II, Portici, Italy

[3]Institute for Agricultural and Forest Systems in the Mediterranean, CNR, Portici, Italy

[4]Centre for Forensic Soil Science, James Hutton Institute, Aberdeen, UK

Correspondence
Giacomo Mele, Institute for Agricultural and Forest Systems in the Mediterranean, CNR, Portici, Italy,
Email: giacomo.mele@cnr.it

Abstract

Soil forensics is not only a well-established research domain but has also been used in numerous successful international searches for burials and as trace evidence to help police and law enforcement in solving criminal, environmental and terrorism investigations. However, despite the confidentiality and legal constraints in case work in many parts of the world, some actual case studies using soil materials as evidence in court hearings have been published in international journals and books. This paper presents a case from the Campania region in Italy where soil analysis played a pivotal role. Employing a multiscale integrated approach encompassing soil microtomography, morphology, chemical analysis and geography, the study aimed to discern the origin of questioned soil residues found on a victim of crime. Results highlight the significance of considering spatial variability and an appropriate choice of analytical methods. The sequential and multiscale approach facilitated timely investigation without incurring unnecessary costs. Soil morphological and chemical analysis revealed inconsistencies between soil on the victim and soil at the suspected crime scenes, narrowing the investigative area down to approximately one square km. While detailed sampling did not yield statistically significant results, the evidence provided crucial insights, aiding investigators in working out what happened and helped in building a narrative around their case. The analysis indicated contact with a primary scene where the victim was likely dragged (over a Calcisol) and a final deposition site (over an Andosol) where the body was found. While potential murder sites were excluded, final guilt attribution remained inconclusive, and as in all trace evidence evaluation, it is not the role of the forensic soil scientist to consider the level of guilt, but to provide factual soil forensic evidence to assist the justice system. This study exemplifies the use of soil forensics in informing criminal investigations and highlights the complexities that can be involved in establishing comparability between soil samples.

KEYWORDS
multiscale soil analysis, soil forensics, X-ray microtomography

1 | INTRODUCTION

The use of soil to assist criminal investigations dates back around 150 years ago (Fitzpatrick et al., 2017) and before that to Roman times when they examined the hooves of enemies' horses to work out where they had travelled from. The use of soils in forensic investigations can provide valuable information due to its variable nature, its transferability, persistence, its often invisible nature, and the ability to ascertain the likely origin of soil traces adherent to a wide range of objects and people, including shoes, tyres, clothes and hair (e.g., Barone et al., 2016; Dawson, 2017; Di Maggio et al., 2017; Donnelly et al., 2019; Donnelly et al., 2021; Fitzpatrick et al., 2009; Fitzpatrick & Donnelly, 2021; Guo et al., 2019; Murray, 2004, 2011; Ruffell & McKinley, 2008; Testoni et al., 2019; Testoni, Dawson, et al., 2022; Testoni, Prandel, et al., 2022). Soil variability results from the result of a combination of soil forming factors, and pedological processes such as the type of underlying geological parent material, position in the landscape, predominant local climate, vegetation, living organisms in the soil, human influences and time (Görres, 2020; Jenny, 1994). Each of these complex factors in turn interacts and results in the formation of specific and often characteristic soil types. When soil is transferred to different types of surface and persists, this can enable detection and recovery, and the questioned sample can be examined and analysed to ascertain likely origin. In addition to morphological (e.g., colour) and texture analysis, chemical extractions have been used in actual forensic investigations where (e.g., Concheri et al., 2011) they have been successfully used for total extraction and elemental analysis through inductively coupled plasma mass spectrometry (ICP-MS) and ICP-optical emission spectrometry (ICP-OES) approaches. Similar experimental cases have also been conducted by Reidy et al. (2013) for inorganic extraction and by Mayes et al. (2009) for organic extractions from soils.

Soil forensics is now a well-established and accepted research domain. It is an important tool in search operations as well as in human taphonomy, and more commonly in trace evidence comparison (Dawson, 2023) such as is described in this paper. However, despite the confidentiality and legal constraints in case work in many parts of the world, successful actual case studies have been published in numerous international journals and books (e.g., Barone et al., 2016; Di Maggio et al., 2017; Donnelly et al., 2019; Donnelly et al., 2021; Fitzpatrick et al., 2009; Fitzpatrick & Donnelly, 2021; Guo et al., 2019; Murray, 2004, 2011; Ruffell & McKinley, 2008; Testoni et al., 2019). The majority of these actual case studies have led to successful convictions (e.g., Concheri et al., 2011 and others). By contrast, very few actual case studies reported on in the literature have been from an unsuccessful conviction in a court of law—with the exception of the case study by Fitzpatrick and Raven (2019). This paper presents an example of where a sequential soil forensic approach integrated with soil microtomography and other special analyses proved to be of use in an actual case in the Campania region in Italy despite being an unsolved murder case.

Highlights

- Unsolved actual cases reported in the academic literature of soil forensics remain limited.
- A multiscale and multianalysis approach is presented, which adapts to the investigation timing and cost limits.
- Geospatial approach helps crime scenes identification while X-ray micro-CT allows accurate characterisation of the main soil findings.
- The soil on the victim's body was incompatible with those of the potential crime scenes.

The aim of this paper is to demonstrate the importance of considering both soil and landscape spatial variability along with choice of analytical method in soil forensics as a sequential and multiscale approach, designed according to the investigative questions and outcomes.

1.1 | The case

A dead body was found by the police lying face down on a dirt forest road near to a playground in a mountain site in the Campania region of southern Italy. The investigative questions were: had the victim been killed at that location? If not, had the victim been moved from a different location? These questions were to help the investigator deduce the location of the death event of the victim. In technical terms, the prosecutor asked if soil science could perform the following tasks (which are connected with specific questions):

Task 1. Identify the nature and type of soil (and identify any retained plant residues) found on the victim's body.
Task 2. Verify the comparability of the soil found on the victim's body with the soil in the specific place where the victim was found.
Task 3. Verify, if possible, whether the body had been dragged and/or transported from a different place, that is, if there were other soil material and botanical traces on the body which could not be explained by the characteristics of the find site.
Task 4. Identify, through comparative analysis with other soils (geographic traceability) the specific place where the victim had likely been killed.

1.2 | The police enquiry

The investigation was complex and had to proceed in stages according to the different tasks to be performed. The results from each step were then used to help to evaluate the subsequent steps.

2 | MATERIALS AND METHODS

Table 1 shows the scheme of the soil analyses carried out according to the investigative questions.

The methods are in agreement with the guidelines established in ENFSI APST WG 'Guidelines on soil examination' (https://enfsi.eu/wp-content/uploads/2017/06/ENFSI_BPM_APST_Soil_Examination-vs1.0.pdf) and the Guide to Forensic Geology (Donnelly et al., 2021) to ensure compliance with best practice.

In addition, all soils (including the samples collected on the victim) were described and sampled using the FAO guidelines (Jahn et al., 2006). Organic carbon was determined using a CHNS analyser (Fisons CHNS/O Analyzer EA1108). All the statistical analysis (basic statistics, ANOVA and Pearson correlation) was performed using SPSS (https://www.ibm.com/spss). Multiple comparisons of means (e.g., Hochberg & Tamhane, 2008) was based on the T-test or the Mann–Whitney test for two independent variables in the case of the Shapiro–Wilk normality test passed or not, respectively.

2.1 | Tasks 1 and 2: Soil analysis of the playground where the victim was found and the soil samples on the victim's body

A small qualitative soil survey examination was first produced at and around the crime scene to evaluate the soil spatial variation locally to help inform an appropriate representative contact reference soil sampling in the playground where the victim was found. Corresponding to A and Bw soil horizons, the soils were described and sampled (A and Bw horizons were sampled at the locations reported in Figure 1a at the following sampling depth: A horizons 0–15 cm, Bw horizons: 15–50 cm) to help understand soil variability across the surface and with depth at the playground site. The soil surface (road pavement) below where the body was found was also sampled.

In addition, questioned (unknown source location) soil samples obtained from the original police investigation were recovered in the laboratory from a range of items: (i) soil adhering to the victim's shoes, (ii) soil residues from under the victim's belt and (iii) soil adhering to the victim's jacket.

On all collected soil samples (5 known reference samples from the crime scene and 41 additional questioned unknown samples from shoes, belt and jacket), X-ray fluorescence (p-XRF) geochemistry was performed. A portable Delta Professional XRF analyser (Olympus, Waltham, MA, USA) was used to measure elemental composition using a relatively large window (8 mm^2) on a smooth uniform

TABLE 1 Investigative questions posed by the public prosecutor of the murder case VS soil analysis carried out.

Task no.	Investigative questions	Soil analysis
1	Victim's body examination	Micromorphological and chemical analysis on victim's body soil and plant residuals collection.
2	Crime scene examination	Preliminary soil survey on crime scene: local spatial variability evaluation to drive sampling for micromorphological and chemical analysis.
3	Is victim's murder place different from the body recovery site?	Deepening of soil structure and plant residuals analysis on victim's body by X-ray microtomography and high magnification microscopy, respectively.
4	If answer to question 3 is 'yes', which the victim's killing place?	Two scales land units identification by sequential GIS-based analysis and multiple statistical geochemical comparison between different soil samples compatible with victim's body soil selected taking also into account for police force information.

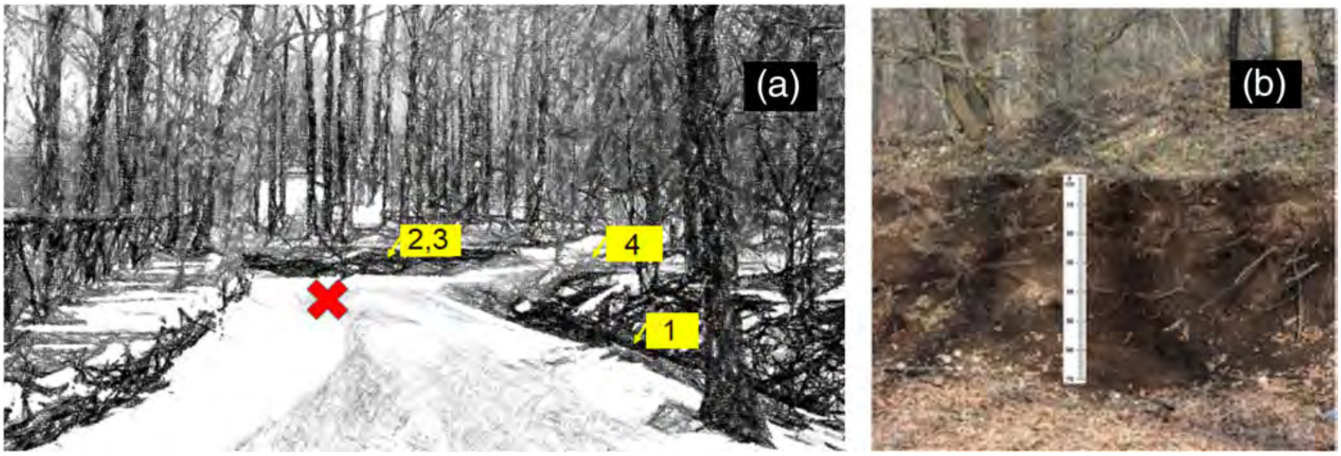

FIGURE 1 (a) Sketch of the crime scene setting (in white due to the snow cover, with a red cross marked as the location of where the body was found). The boxes in yellow denote the reference sampling locations. (b) A soil profile (from location 1) at the crime scene showing the dark A horizon.

surface, in order to enable good contact between the instrument and the sample surface, and to minimise surface effects. In selected cases, to avoid contamination due to human artefacts (e.g., a soil aggregate behind the belt potentially contaminated by the belt itself), the p-XRF analysis was performed at an inner freshly exposed surface of aggregates. The instrument features an Ag X-ray tube operated at 15–40 kV with integrated large area silicon drift detector (165 eV). The Innov-X software was used in Soil and Mining mode (acquisition times of 30 s per beam).

2.2 | Task 3: Verify, if possible, whether the body had been dragged and/or transported from a different place to the body recovery site

This task was addressed through a detailed analysis of soil and plant fragments found on the victim's body. Both soil X-ray microtomography and visual identification of plant fragments through stereomicroscopy were carried out.

2.2.1 | Detailed soil analysis

A micromorphological and microtomographic analysis was carried out on the soil fragments extracted from material adhering to the inside and just below the victim's belt. The X-ray micro-CT scans were performed using a desktop microtomograph (Bruker Skyscan 1272; http://bruker-microct.com/products/1272.htm). It was equipped with a cone beam X-ray source adjustable in the 20e100 kV energy range, which allows a cylinder-shaped volume of 6.5 cm in diameter and 7.2 cm height as maximum sample size.

2.2.2 | Analysis of plant residues

An additional analysis was performed on any plant residues present in the soils on the victim's shoes and belt, with residues being identified. Only 5 fragments of wood were collected and studied because they were suitable (in terms of state of conservation and size of fragment) to allow a full analysis of the woody tissue, which differs from taxon to taxon, enabling us to identify to genus and species level. From each sample, the three fundamental observation planes (transversal, radial and longitudinal tangential) were obtained for the study of the anatomy of the wood. Identification was carried out using various identification keys (e.g., Dallwitz et al., 1995; Heiss et al., 2005; Wheeler, 2011) and by comparing anatomical descriptions and descriptions of known species reported in various wood anatomy atlases (Abbate Edlmann et al., 1994; Greguss, 1955, 1959), as well as with samples from the reference collection housed in the Laboratory of Vegetation History and Wood Anatomy at the Department of Agriculture, University of Naples Federico II.

2.3 | Task 4: Identify, through comparative analysis with other soils, (geographic traceability) the place where the victim was likely killed

Geographical Information Systems (GIS)-based analysis using *ArcGIS* 10.3.1 (www.arcgis.com) was carried out by implementing two sequential steps. This analysis was performed over a spatial extension pre-determined by the police force (locations ascertained from the records of signals from the victim's cell phone which all lay within a specific geographic boundary that became the outer boundary of the geospatial analysis).

In addition, after their own investigation, the police suggested a set of specific locations considered as potential candidate locations for the site where the victim had been killed.

2.3.1 | Step 1

A preliminary land unit screening to evaluate the main land units on which to focus the survey was carried out. A geospatial analysis of the main land units of the area was performed by processing the following information: geology (geological map 1: 50,000; at https://www.isprambiente.gov.it/Media/carg/449_AVELLINO/Foglio.html), land use (https://sinacloud.isprambiente.it/portal/apps/webappviewer/index.html?id=885b933233e341808d7f629526aa32f6) and a map of landforms (1:50,000 produced within this specific work).

2.3.2 | Step 2

New sequential sampling focused on only comparable land units with soil from the victim's belt. This sampling was performed in two steps: eight new soil samples were first collected and analysed (using the same morphological and geochemical characteristics carried out for tasks 1 and 2) for locations selected after the police investigation, to identify a compatible soil map unit, then an additional six soils were sampled and analysed at a specific site, which appeared to have similar soil to that from the victim's belt. A statistical multiple comparison between geochemical data of the newly sampled soils and the soil from the victim's belt was carried out.

3 | RESULTS AND DISCUSSION

In Table 2 are some key soil parameters reported after the soil description and characterisation.

3.1 | Tasks 1 and 2: Soil analysis of the playground where the victim was found and the soil samples on the victim's body

The soil spatial variability around the crime scene was considered homogeneous. Figure 1a is a sketch of the crime scene setting characterised by a dense beech forest, a playground and forest roads covered in snow. A typical soil profile is shown in Figure 1b; the black soil colour (7.5 YR 2,5/1) clearly highlights soils that are high in organic matter content.

In Figures 2 and 3 (reported below), the comparison between the samples obtained from the victim's belt, shoes and jacket and the samples collected at the playground (the place where the victim's body was found) are shown. All comparisons, including those related to uranium (U), thorium (Th) and potassium (K) percentages and those relating to calcium (Ca) percent, indicate geochemical incompatibility between the playground soils (including the road surface) and those found on the victim. Furthermore, the playground soils were statistically different (difference between means: ANOVA; $p < 0.001$) from both (i) the soil aggregate (named 'ped' in the figures) found on the victim's shoes (regarding the following chemical elements: K, Zr, Sr, Nb and Pb) and (ii) soil aggregate found under the victim's belt (regarding the following chemical elements: Ca, Fe, V, Zn, Nb and Pb).

The data provided through soil morphology and geochemistry clearly show the incompatibility between the soils of the playground site and the soils found on the victim's body. The playground soils range from dark (7.5 YR 2.5/1) to brown (7.5 YR 4/4) in colour, all with a high organic matter content, and most importantly, they have no carbonate present (tested by the application of HCl to a part of the sample) or the absence of carbonate concretions. On the contrary, the soils found on the victim's body are very pale in colour (e.g., 2.5 Y 5/3), low in soil organic matter and have small calcium carbonate concretions present.

These differences are marked further if we observe the geochemical difference between the soils found on the body and those sampled at the playground. Figure 2 highlights the incompatibility of the geochemical signals of thorium, uranium and potassium between the two soil sample types.

In pedological terms, the playground site has a specific type of soil called Andosol in accordance with the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2022). This is a volcanic soil with a high degree of paedogenetic development. In Campania, Andosols have some specific chemical characteristics such as a clearly detectable content (5–40 ppm) of thorium and uranium (green bars, Figure 2) due to the presence of these elements in the volcanic ash of the great Plinian eruptions of Campi Flegrei (e.g., Neapolitan Yellow Tufo) and Vesuvius (e.g., Pomici di Avellino). Figure 2 clearly shows that the playground soils have a moderate content (5–40 ppm, i.e. 0.0005%–0.004%) of thorium (red bars in Figure 2) and uranium (green bars in Figure 2), whereas these two elements are absent (the figure does not show green and red bars) in all the soil microsamples found on the body (belt, shoes and

TABLE 2 Soil morphological analysis.

Location	Coarse fragments %	Coarse fragment size	Colour (Munsell chart)	Colour description	HCl reaction test
Shoes (victim)	5	5 mm	2.5 Y 5/3	Light olive brown	Calcareous
Belt (victim)	Absent	Absent	2.5 Y 5/3	Light olive brown	Calcareous
Playground soil 1 (A horizon)	1	5 mm	7.5 YR 2,5/1	Black	Non-calcareous
Playground soil 2 (A horizon)	1	5 mm	7.5 YR 2,5/1	Black	Non-calcareous
Playground soil 3 (B horizon)	2	5 mm	7.5 YR 4/4	Brown	Non-calcareous
Playground soil 4 (B horizon)	35	7 mm	10 YR 4/4	Dark yellowish brown	Non-calcareous

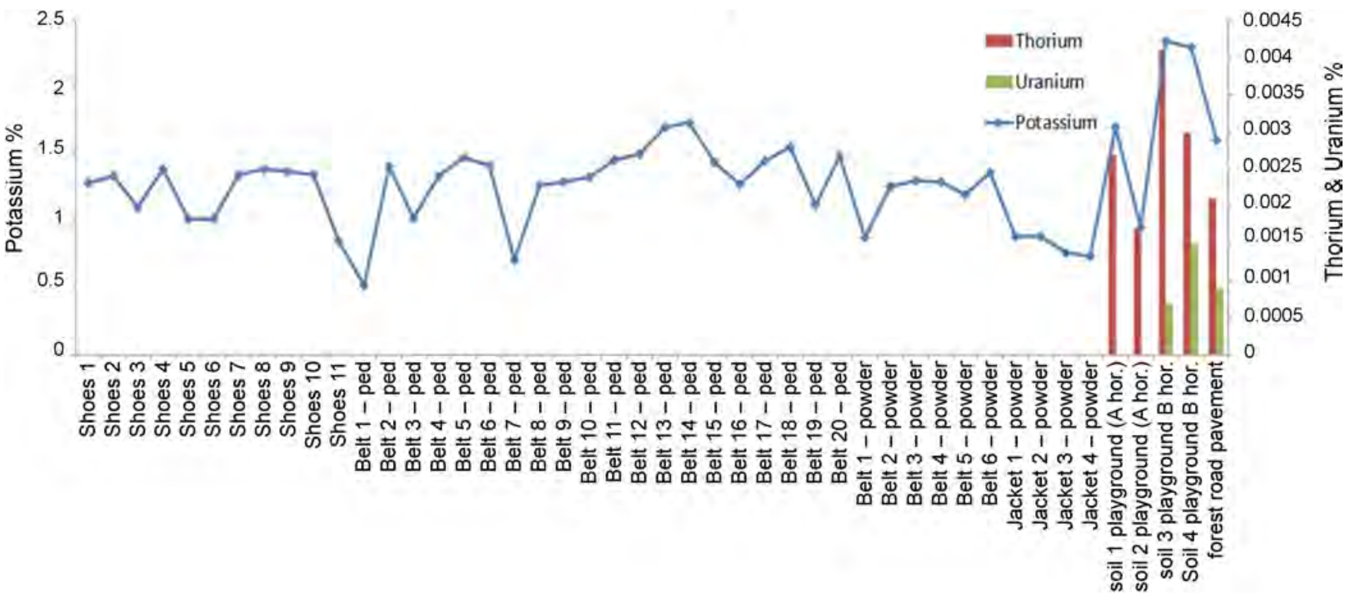

FIGURE 2 Potassium (K) content (%) on the left y-axis and Uranium (U) and Thorium (Th) content (%).

jacket). Furthermore, as one would expect from soils of volcanic origin, the K content is generally high in the playground soils, higher than in the soils found on the victim's body.

Finally, the soils of the playground have a low calcium content (1%–3%), while the soil samples on the victim's body have a calcium content (5%–9%) higher than those of the playground (Figure 3).

Due to the gravel, the analysis of the surface sample obtained in the playground (the surface where the victim's body was found lying) shows a high calcium content, but also a detectable content (last bar) of thorium and uranium (absent in the soils found on the victim's body).

In summary, all the evidence show that the soil found on the victim body has a very different origin from the Andosols found in the playground. The questioned soil recovered from the victim's body can therefore be excluded as sharing a common origin with soils from the playground site.

3.2 | Task 3: Verify, if feasible, whether the body had been dragged and/or transported from a different place to the body recovery site

Figure 4 reported below shows an example of the largest aggregate (almost 3 cm in diameter) found below the victim's belt. The image on the left of the figure shows a view from above, while the other part of the figure shows a cross-section of the aggregate with evidence of microlaminations.

X-ray microtomography permitted a more in-depth analysis of the internal microstructure of the aggregate. In Figure 5 below, an internal section of the aggregate is shown. The red arrows show the presence of sub-horizontal vesicular and planar pores (seen as black pores). These pores are clear proxies indicating an evident energetic compression of the soil sample. This finding is also confirmed by the evidence of a high degree of soil compaction in the middle of the soil specimen (paler grey colour matrix).

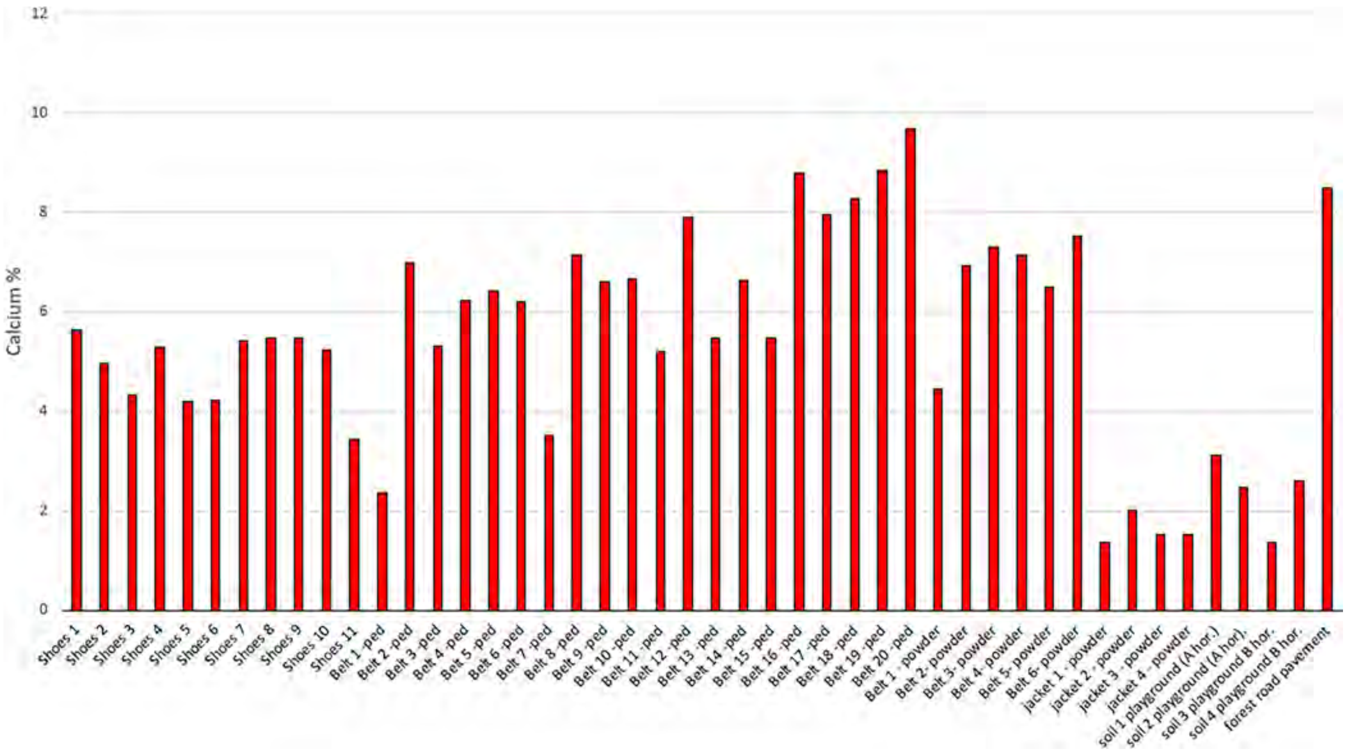

FIGURE 3 Calcium content (%) variability between the different soil samples and the playground soils (labels on the right-hand side of the x-axis).

The result, which emerged from the microscope analysis of the anatomy of the collected wood fragments and using various identification keys, was that all the woody residues (Figure 6) were of the tree species hazel (*Corylus avellana*).

This investigation highlighted the fact that the soil under the belt was highly compacted. In other words, this soil did not simply fall inside the victim's belt, but instead entered and was compressed, most likely following an energetic dragging of the victim (in a prone position) over a (clayey) wet soil with a subsequent period of drying in situ. In addition, the plant residue recovered from the victim had nothing to do with the beech trees, which were found around the forest playground (they were hazel). At the same time, the residue is compatible with other land use units in the area, where the species *hazel* is widely distributed.

3.3 | Task 4: Identify, through comparative analysis with other soils, (geographic traceability) the place where the victim was likely killed

3.3.1 | Step 1

First step of GIS-based analysis made it possible to produce a map of the land systems including basic pedological information, (i) enabling us to exclude land units with very different soils from those found on the victim's body and (ii) acting as an initial step which would orientate new soil sampling towards the identification of the crime scene location. The area had the following land systems, which included the spatial distribution of soil types in accordance with the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2022).

1. Low hills of Irpinia with a covering of pyroclastic materials (Molli-Vitric Andosols).
2. Marly-calcareous and marly-sandstone hills of Irpinia and Sannio (Haplic Calcisols).
3. Alluvial plain of the Volturno river (Fluvisols).
4. High altitude slopes of limestone reliefs covered by ashfall deposits (Mollic-vitric Andosols).
5. Low altitude slopes of limestone reliefs covered by ashfall deposits (Mollic-vitric Andosols).

The land unit map reported in Figure 7 shows the spatial distribution of these systems.

On the basis of the pedological criteria, the land mapping units 1, 3, 4, 5 were excluded from further consideration as they were not compatible with the type of soils found on the victim's body. Thus, the only map unit suitable for additional soil analysis was number 2, namely ‘Marly-calcareous and marly-sandstone hills of Irpinia

FIGURE 4 Photographs of the victim's belt (top). The lower left and right images represent soil aggregate recovered from the rear of the victim's belt.

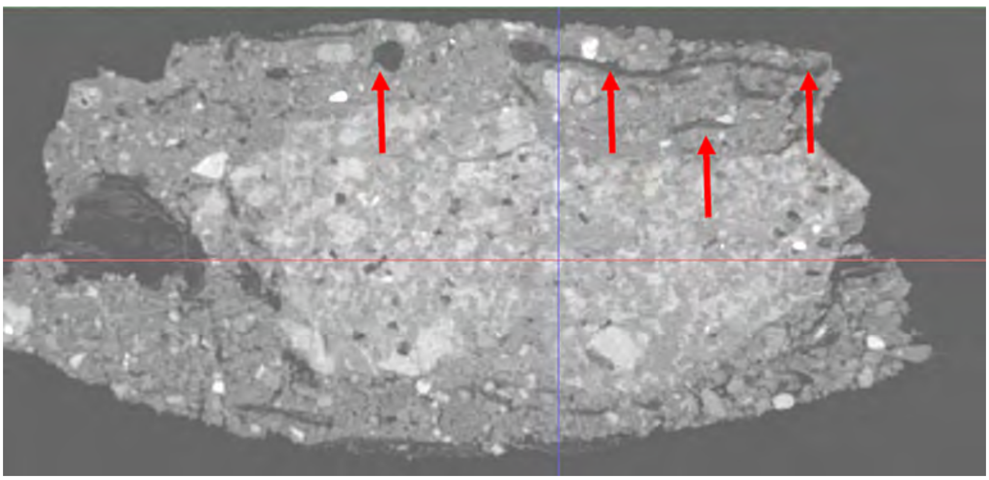

FIGURE 5 X-ray microtomography of the soil aggregate recovered from behind the victim's belt.

and Sannio', with Haplic Calcisols (IUSS Working Group WRB, 2022) as reference soils.

3.3.2 | Step 2

New sequential sampling focused therefore on the land area represented by number 2 soils, the only compatible land unit. Morphological and geochemical results from these investigations highlighted the presence of one site (named 'Agritourism A′ on Figure 8), which contained the soils with the morphological and geochemical signals closest to those of the soils found on the body of the victim.

On the basis of these findings, an additional six soils were sampled and analysed at the specific site under consideration (the agritourism farm, Figure 9), which appeared to have similar soil to that from the victim's belt (Agriturismo C, 33,34,35,36,37).

By looking at steps 1 and 2 together, we can draw the following conclusions on the basis of the geochemical comparison of the soil found on the victim with the 15 soils sampled during the investigations. In Figure S1 (Supplementary material), a comprehensive overview of all these data is given showing the main distributions (95% of the distribution; with mean values represented as dots) of the most important chemical elements. In general terms, all the diagrams show a marked differentiation between soil samples in terms of content and distribution of chemical elements.

For many macro-elements (e.g., K, Fe) and micro-elements (e.g., As), the soils extracted from the victim's belt and shoes are similar. This, though, is not true for the

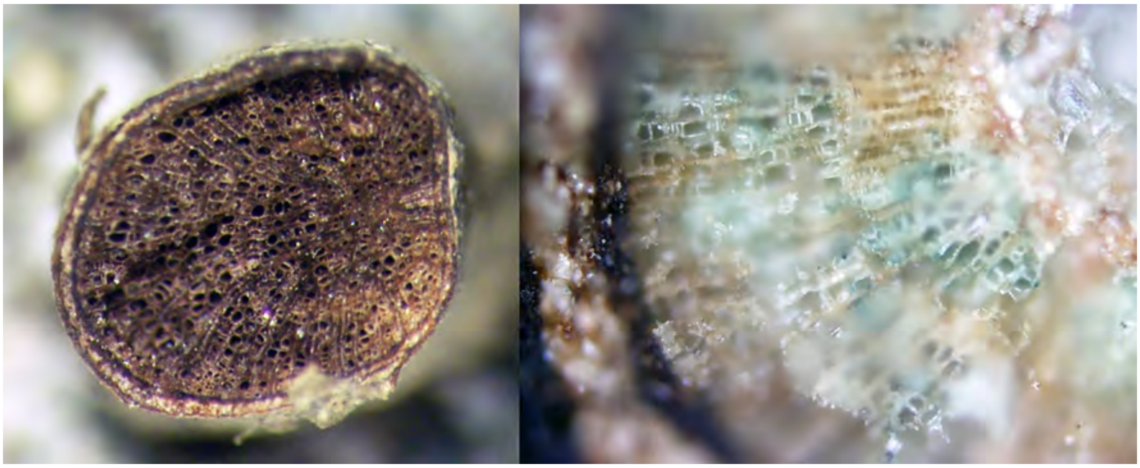

FIGURE 6 Microscopy of plant residues. Left image: Cross-section viewed under a stereomicroscope at 40X magnification. Right image: Cross-section observed under a reflected light microscope at 100X magnification (courtesy of E. Allevato).

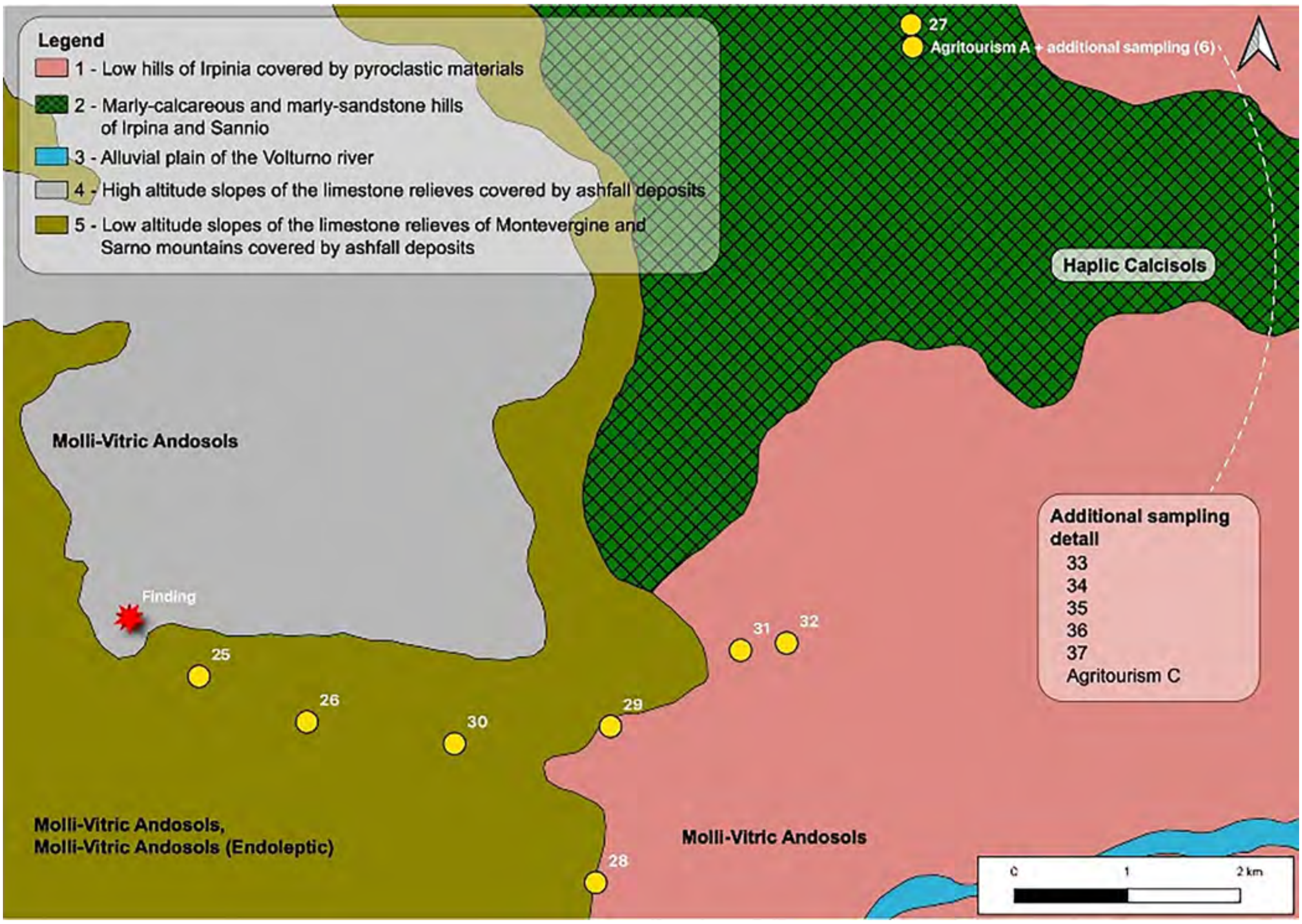

FIGURE 7 Map of land systems. Land system 2 (green with cross bars) is the main land system of interest Haplic Calcisols (IUSS Working Group WRB, 2022).

calcium content (Ca in the figure below). The calcium content is higher in the soil from the belt than in from the shoes. The difference is statistically significant ($p < 0.001$) and shows that the shoes must have picked up soil from another location not comparable with where the soil that was picked up on the belt.

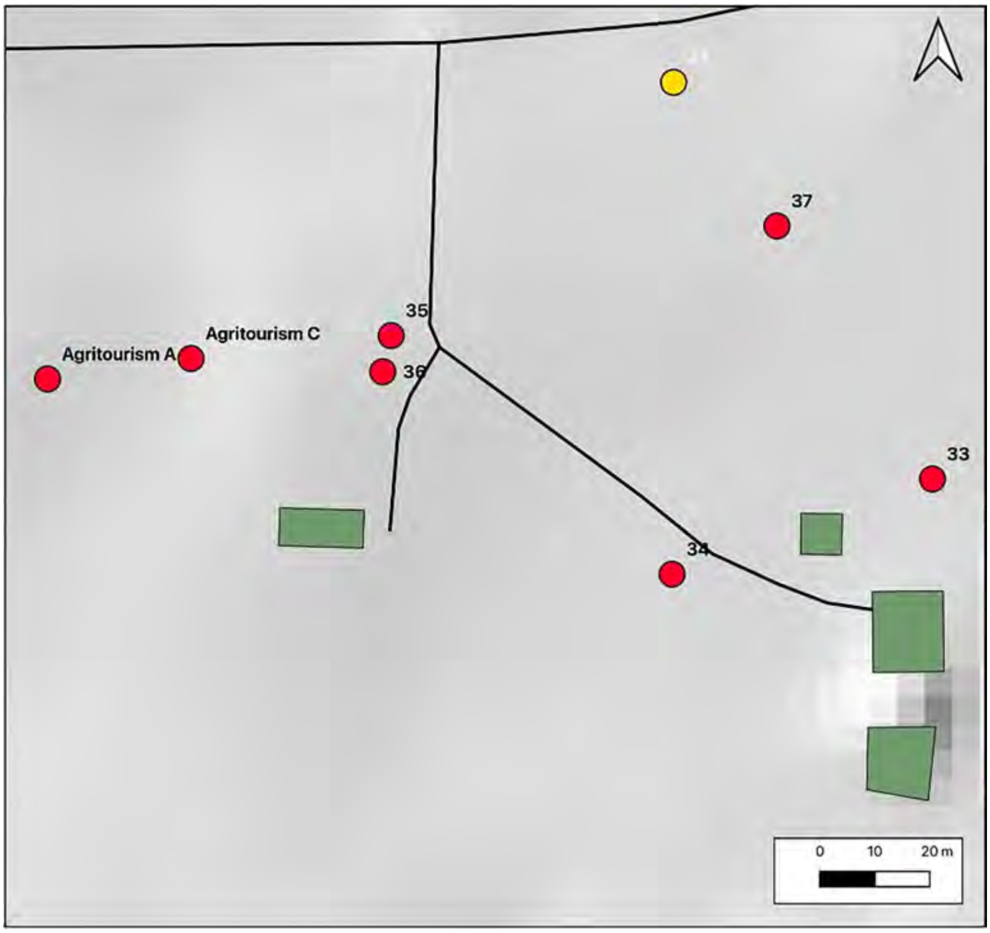

FIGURE 8 Map showing soil sampling points at the Agritourism farm.

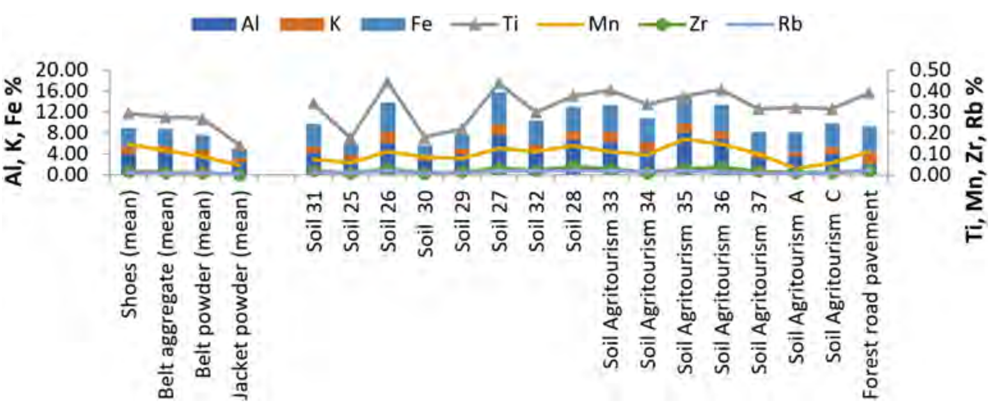

FIGURE 9 Geochemical variability of Fe, K, Al, Ti, Mn, Zr and Rb contents (%) between soil samples collected from items from the victim and reference samples.

For each soil sample, p-XRF was performed to obtain the elemental content of 33 chemical elements, although here we only report results for the most distinguishing elements. A Pearsons correlation analysis was performed over the entire dataset. A set of correlations with a coefficient of $p < 0.01$ between chemical elements permitted the separation of two geochemical settings: elements whose concentration is associated with Fe-based soil formation processes (Fe is a key element in soil formation). As expected, Fe correlates well with Ti (0.77) and Mn (0.55) because of their similar ionic potentials, but, most interestingly, Fe also correlates positively with Al (0.75), K (0.81), Zr (0.82) and Rb (0.72). The behaviour of the latter is most likely connected with the mineralogy of the soil samples. For example, the occurrence of feldspar in volcanic soils may well explain the positive correlation between K and Al.

Of the elements whose concentration is associated with Ca-based soil formation processes, Ca correlates with Zn (0.32), S (0.37) and Se (0.45). This geochemistry depicts a calcium-dominated environment such as soils rich in calcium carbonate, and this occurs in a few of the samples analysed.

Figure 9 shows the mean content (%) of Fe, K, Al, Ti, Mn, Zr and Rb associated with Fe-based soil formation processes. On the left-hand side of the figure, the soils found on the victim are presented. From the results, it is evident that most of the sites differ in their chemical composition with respect to the soil samples found on the victim. In particular, the samples most similar to those found on the victim's belt (the most diagnostic ones for the purposes of this investigation) were Agritourism 37, Agritourism A and Agritourism C.

In terms of calcium carbonate geochemistry, Figure 10 shows the mean content (%) of calcium and Zn. The samples from most of the sites have a markedly different calcium content compared with the soil samples found on the victim.

From an analysis of the distribution of the calcium content (and of the associated elements), it can be seen that the samples most similar to those found on the belt were: Agritourism 34 and Agritourism 37.

If we consider all the samples taken at the farm and look at the statistical significance of the differences ($p < 0.05$) between the chemical composition of these samples and the chemical composition of the soil found under the victim's belt, we obtained the results reported in Table 3 (complete statistical results are in the Data S1).

From Table 3, the comparative analysis shows that by considering the content of potassium, calcium, iron and manganese, it is possible to exclude many of the reference soils sampled with the soil found under the belt, as they are different. Based on the highest number of elements exhibiting statistically similar content, the 'Agritourism farm 37' soil sample resulted in the closest value to the belt sample. Four elements (Al, K, Ca and Sr) 'Agritourism farm 37' soil sample still exhibit statistically different content of a total of the 11 elements considered.

Overall, statistical analyses of geochemical measurements indicate the 'Agritourism farm 37' specific soil sample as the soil sample most similar to the 'belt' sample, but it was not the same. On the contrary, the soil collected behind the victim's belt from a geochemical point of view is *de facto* different from the soils sampled in the compatible points indicated as Agritourism. Thus, despite some similarity, it is important to emphasise that a perfect 'match' or high degree of 'comparability' of the soils found on the body and the Agritourism soils was not found, thus it is impossible to identify the specific place where the victim had likely been killed. However, as

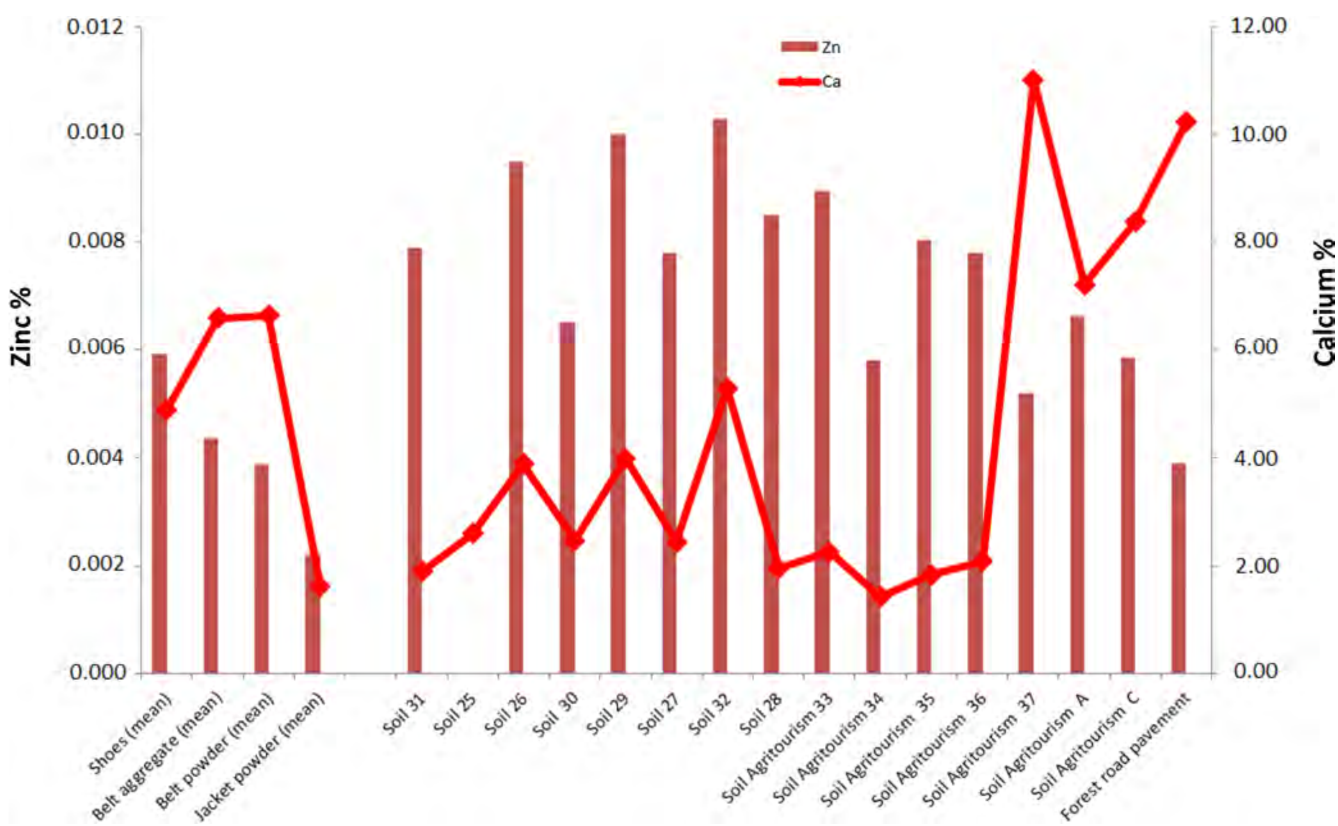

FIGURE 10 Geochemical variability of Ca (ppm) red line and Zn (%) dark red bars.

TABLE 3 Outcomes (*p*-values) of statistical tests of mean content comparison of chemical elements between the soil samples and the questioned sample recovered from the victim's belt.

	Al-MP	K-MP	Ca-MP	Mn-MP	Fe-MP	Zr-MP	Ti-SO	V-SO	Rb-SO	Sr-SO	Zr-SO	#
Agr 33	0.00531	0.00028	0.00001	0.68767*	0.00001	0.00001	0.02334	0.02334	0.02334	0.02334	0.02334	1
Agr 34	0.85473*	0.06142*	0.00666	0.48173*	0.00016	0.49161*	0.00001	0.00416	0.00001	0.00246	0.84351*	5
Agr 35	0.00002	0.00990	0.00001	0.07044*	0.00001	0.00001	0.00001	0.00001	0.00665	0.00003	0.00001	1
Agr 36	0.00056	0.08563*	0.00001	0.06110*	0.00001	0.00001	0.00001	0.00001	0.15628*	0.26489*	0.00001	4
Agr 37	0.03517	0.00141	0.00009	0.68767*	0.12990*	0.14839*	0.21716*	0.79308*	0.24909*	0.00004	0.24882*	7
Agr A	0.04417	0.00001	0.75865*	0.00087	0.06260*	0.02848	0.25056*	0.45824*	0.00011	0.15931*	0.00001	5
Agr C	0.22062*	0.22705*	0.03815	0.00582	0.00002	0.05031*	0.00006	0.19691*	0.00001	0.23496*	0.00724	5

Note: # Number of chemical elements statistically equal to the soil samples from the belt.
*p-value > significance level ($p = 0.05$).

stated by Robertson (2009), there is no such thing as a 'match' with soil samples but the determination of similarities, based on the evidence that a questioned sample was more likely to have originated from a known location than from an alternative proposition source location as dictated by the individual case context. Such an evaluation was not carried out at the time of this investigation.

Nonetheless, it is necessary to stress that none of the specific sampling points investigated at the maximum level of detail produced a result that was a statistical equivalence to any of the soil found on the victim's body. Therefore, perfect comparability between the soil recovered from the body and the soils sampled by the police during this investigation was not shown. However, as a result of potential mixing and difficulty of single source sampling, it is very unlikely that there would ever be an absolute high degree of comparability. Of course, these findings may be affected by different factors such as the soil spatial variability at local scale or elemental concentration/dilution by the impact activity (despite the caution highlighted in the material and methods section).

4 | CONCLUSION

This paper highlights (i) the usefulness of a deterministic nested geospatial approach in which three sampling phases were carried out with the aim of identifying a crime scene by taking successive steps and (ii) the use of X-ray microtomography, which allowed a detailed analysis of the soil aggregates found under the victim's belt. This analysis made it possible to show a marked compaction of the soil aggregates consistent with those caused by a dragging of the victim along the ground.

At the end of the investigation, it was possible to demonstrate (a) the pedological incompatibility between the composition of the soil on the victim's body and many of the sites considered as potential crime scenes, and (b) it was possible to restrict the area for consideration to within an area of about one square kilometre.

Further investigations with (i) more, better-targeted individual source samples and with (ii) the aid of satellite images (and their processing for the classification of the areas in this case with *hazel* trees) might have allowed us to get closer to identifying the as yet unknown primary crime scene. In addition, if the later phases of the work could have been carried out nearer to the time the crime was committed, the investigation might have yielded a more accurate sampling of the farm site.

Nevertheless, this soil forensic investigation provided valuable information to the investigators, which assisted them in their enquiries. The prosecutor used the evidence obtained to build his case, as the soil and plant residues indicated that there had indeed been a primary scene where the victim was likely dragged to that location, followed by a final deposition site where the body was found. The primary outcome of this analysis was to exclude potential murder sites and—possibly—to exclude a potentially inappropriate guilty verdict for the murder of the victim.

AUTHOR CONTRIBUTIONS

F. Terribile: Conceptualization; methodology; writing – original draft; investigation; writing – review and editing; supervision. **M. Iamarino:** Visualization; data curation. **G. Langella:** Visualization; data curation. **Giacomo Mele:** Formal analysis; data curation; writing – review and editing; methodology; supervision. **L. Gargiulo:** Visualization; data curation. **F. A. Mileti:** Investigation; visualization; data curation. **S. Vingiani:** Investigation; data curation. **L. Dawson:** Supervision; writing – review and editing.

ACKNOWLEDGEMENTS

We wish to thank Dr. Emilia Allevato for the analysis of plant residues, the Public Prosecutor's Office of Naples for granting permission for the publication of this work and, finally, the anonymous Reviewer whose accurate and exhaustive reviews were crucial in the re-casting of the paper, greatly enhancing its quality and coherence.

CONFLICT OF INTEREST STATEMENT

Permission to reproduce material from other sources has been required and obtained as indicated in the text of the manuscript.

DATA AVAILABILITY STATEMENT

The data that supports the findings of this study are available in the supplementary material of this article.

ORCID

F. Terribile https://orcid.org/0000-0003-3672-2294
G. Langella https://orcid.org/0000-0001-7210-0906
Giacomo Mele https://orcid.org/0000-0003-4184-8166
L. Gargiulo https://orcid.org/0000-0001-6357-7446
F. A. Mileti https://orcid.org/0000-0002-3899-7622
S. Vingiani https://orcid.org/0000-0002-3543-8438
L. Dawson https://orcid.org/0000-0002-8125-2458

REFERENCES

Abbate Edlmann, M. L., De Luca, L., & Lazzeri, S. (1994). Atlante anatomico degli alberi ed arbusti della macchia mediterranea. Relazioni e monografie agrarie subtropicali e tropicali nuova serie No. 114, Istituto Agronomico per l'oltremare. Firenze.

Barone, P. M., Di Maggio, R. M., & Ferrara, C. (2016). Forensic geoscience during CS investigations and courtroom trials without a murder. *Journal of Forensic Science & Criminology*, *4*(3), 302. https://doi.org/10.15744/2348-9804.4.302

Concheri, G., Bertoldi, D., Polone, E., Otto, S., Larcher, R., & Squartini, A. (2011). Chemical elemental distribution and soil DNA fingerprints provide the critical evidence in murder case investigation. *PLoS One*, *6*(6), 4–8. https://doi.org/10.1371/journal.pone.0020222.2

Dallwitz, M. J., Paine, T. A., & Zurcher, E. J. (1995). Onwards. User's guide to Intkey: a program for interactive identification and information retrieval. http://delta-intkey.com

Dawson, L. (2023). Soil science in the criminal justice system. In M. J. Goss & M. Oliver (Eds.), *Encyclopedia of soils in the environment* (Vol. 3, Second ed., pp. 521–531). Academic Press. https://doi.org/10.1016/j.forsciint.2016.12.004.10

Dawson, L. A. (2017). Soil organic characterisation in forensic case work. *International Journal of Geosciences*, *40*(2), 157–165. https://doi.org/10.18814/epiiugs/2017/v40i2/017018.3

Di Maggio, R. M., Donnelly, L., Al Naimi, K., Barone, P. M., Salvador, F., Dawson, L. A., Dixon, R., Fitzpatrick, R. W., Gradusova, O., Nesterina, E., Peleneva, M., Ushacova, O., Molina, C. M., Pirrie, D., Ruffell, A., McKinley, J., Sagripanti, G., Villalba, D., Schneck, B., … Forbes, S. (2017). Global developments in forensic geology. *Episodes*, *40*(2), 120–131. https://doi.org/10.18814/epiiugs/2017/v40i2/017014

Donnelly, L. J., Cassella, J., Pirrie, D., Dawson, L., Blom, G., Davidson, A., Arnold, P., Harrison, M., & Hope, C. (2019). Analysis of soil following a police-led open area search and the recovery of a cold case homicide grave. In R. W. Fitzpatrick & L. J. Donnelly (Eds.), *Forensic soil science and geology. Geological society* (p. 492). Special Publications. https://doi.org/10.1144/SP492-2017-337

Donnelly, L. J., Pirrie, D., Harrison, M., Ruffell, A., & Dawson, L. A. (2021). *A guide to forensic geology*. Geological Society London. https://doi.org/10.1144/GFG

Fitzpatrick, R. W., & Donnelly, L. J. (2021). Introduction to forensic soil science and geology: A synthesis. In R. W. Fitzpatrick & L. J. Donnelly (Eds.), *Forensic soil science and geology* (p. 492). Geological Society, London, Special Publications.

Fitzpatrick, R. W., & Raven, M. D. (2019). The forensic comparison of trace amounts of soil on a pyjama top with hypersulfidic subaqueous soil from a river as evidence in a homicide cold case. In R. W. Fitzpatrick & L. J. Donnelly (Eds.), *Forensic soil science and geology* (p. 492). Geological Society London Special Publications. https://doi.org/10.1144/SP492-2019-59

Fitzpatrick, R. W., Raven, M. D., & Forrester, S. T. (2009). A systematic approach to soil forensics: Criminal case studies involving transference from crime scene to forensic evidence. In K. Ritz, L. Dawson, & D. Miller (Eds.), *Criminal and environmental soil forensics* (pp. 105–127). Springer Science Business Media B.V. https://doi.org/10.1007/978-1-4020-9204-6_8

Fitzpatrick, R. W., Raven, M. D., & Self, P. G. (2017). The role of pedology and mineralogy in providing evidence for 5 crime investigations involving a wide range of earth materials. *Episodes Journal of International Geoscience*, *40*(2), 148–156. https://doi.org/10.18814/epiiugs/2017/v40i2/017017

Görres, J. H. (2020). Soil: spatial variability. In *Landscape and land capacity* (pp. 283–295). CRC Press.

Greguss, P. (1955). *Identification of living Gymosperms on the basis of xylotomy*. Akadémiai Kiadò.

Greguss, P. (1959). *Holzanatomie der Europäischen laubhölzer und sträucher*. Akademial Kiado.

Guo, H., Wang, P., Hu, C., Zhu, J., Yang, X., Quan, Y., Mei, H., & Li, J. (2019). A case study in forensic soil examination from China. In R. W. Fitzpatrick & L. J. Donnelly (Eds.), *Forensic soil science and geology* (p. 492). Geological Society London, Special Publications. https://doi.org/10.1144/SP492-2017-307

Heiss, A. G., Kofler, W., & Oeggl, K. (2005). *The Ulten Valley in South Tyrol, Italy: Vegetation and settlement history of the area, and macrofossil record from the Iron Age Cult Site of St. Walburg*. (Vol. 1, pp. 63–73). Palyno-bulletin of the Institute of Botany, University of Innsbruck, 1, 63–73.

Hochberg, Y., & Tamhane, A. C. (2008). *Multiple comparison procedures*. John Wiley & Sons, Inc. Book Series: Wiley Series in Probability and Statistic, ISBN: 978-0-470-31667-2.

IUSS Working Group WRB. (2022). *World Reference Base for soil resources. International soil classification system for naming soils and creating legends for soil maps* (4th ed.). International Union of Soil Sciences (IUSS).

Jahn, R., Blume, H. P., Asio, V. B., Spaargaren, O., & Schad, P. (2006). *Guidelines for soil description*. Fao.

Jenny, H. (1994). *Factors of soil formation: A system of quantitative pedology*. Courier Corporation.

Mayes, R. W., Macdonald, L. M., Ross, J. M., & Dawson, L. A. (2009). Discrimination of domestic garden soils using plant wax compounds as markers. In D. L. RitzK & D. Miller (Eds.), *Criminal and environmental soil forensics* (pp. 463–767). Springer.

Murray, R. C. (2004). *Evidence from the earth: Forensic geology and criminal investigation* (First ed.). Mountain Press Publishing.

Murray, R. C. (2011). *Evidence from the earth: Forensic geology and criminal investigation* (Second ed.). Mountain Press Publishing.

Reidy, L., Bu, K., Godfrey, M., & Cizdziel, J. V. (2013). Elemental fingerprinting of soils using ICP-MS and multivariate statistics: A study for and by forensic chemistry majors. *Forensic Science International*, *233*(1–3), 37–44. https://doi.org/10.1016/j.forsciint.2013.08.019.4

Robertson, J. (2009). "Soils Ain't soils": Context and issues facing soil scientists in a forensic world. In K. Ritz, L. Dawson, & D. Miller (Eds.), *Criminal and environmental soil forensics*. Springer. https://doi.org/10.1007/978-1-4020-9204-6_1

Ruffell, A., & McKinley, J. (2008). *Geoforensics*. John Wiley and Sons, Ltd.

Testoni, S., Dawson, L., Melo, V., Lopes-Mazzetto, J., Ramalho, B., & Salvador, F. (2022). Soil colour and plant-wax markers: Application in forensic investigations under urban subtropical environments. *Forensic Science*, *2*(1), 57–71. https://doi.org/10.3390/forensicsci2010005

Testoni, S., Prandel, L. V., Dawson, L., da Silva, A., & Salvador, F. (2022). Conjunctive use of synchrotron X-ray diffraction and Rietveld refinement in Fe-oxide clays for forensic applications. *Journal of Forensic Sciences*, *67*(5), 2020–2031. https://doi.org/10.1111/1556-4029.15098

Testoni, S. A., Melo, V. F., Dawson, L. A., Salvador, F. A. S., & Prandel, L. V. (2019). Evaluation of forensic soil traces from a crime scene: Robbery of a safety deposit box in Brazil. In R. W. Fitzpatrick & L. J. Donnelly (Eds.), *Forensic soil science and geology* (p. 492). Geological Society, London Special Publications. https://doi.org/10.1144/SP492-2019-35

Wheeler, E. A. (2011). Inside Wood–A web resource for hardwood anatomy. *Iawa Journal*, *32*(2), 199–211.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Terribile, F., Iamarino, M., Langella, G., Mele, G., Gargiulo, L., Mileti, F. A., Vingiani, S., & Dawson, L. (2024). Integrated, multiscale forensic soil science applied to an unsolved murder case in Italy. *European Journal of Soil Science*, *75*(6), e70019. https://doi.org/10.1111/ejss.70019