Science & Justice 62 (2022) 229–238

Contents lists available at ScienceDirect

Science & Justice

journal homepage: www.elsevier.com/locate/scijus

Use of Bayesian networks in forensic soil casework

S.C.A. Uitdehaag [a,b,*], T.H. Donders [b], I. Kuiper [a], F. Wagner-Cremer [b], M.J. Sjerps [a,c]

[a] Netherlands Forensic Institute, P.O. Box 24044, 2490 AA The Hague, The Netherlands
[b] Utrecht University, Department of Physical Geography, P.O. Box 80115, 3508 TC Utrecht, The Netherlands
[c] Korteweg-de Vries Instituut, Faculty of Science, P.O. Box 94248, 1090 GE Amsterdam, The Netherlands

ARTICLE INFO

Keywords:
Soil comparison
Bayesian network
Evaluate propositions
Activity level
Source level
Palynology
Elemental composition
Distance measure

ABSTRACT

Forensic soil comparisons can be of high evidential value in a forensic case, but become complex when multiple methods and factors are considered. Bayesian networks are well suited to support forensic practitioners in complex casework. This study discusses the structure of a Bayesian network, elaborates on the in- and output data and evaluates two examples, one using source level propositions and one using activity level propositions. These examples can be applied as a template to construct a case specific network and can be used to assess sensitivity of the target output to different factors and identify avenues for research.

1. Introduction

Soil traces are commonly encountered in forensic investigations on various questioned items and are often overlooked by perpetrators, making them very useful forensic traces. Soil is a complex mixture of different components and thus provides a wide array of possibilities for soil comparison methods. The specific properties of soil samples encouraged many studies on methods to compare soil from a questioned item to soil samples from a location where a criminal activity occurred, using either the composition of the whole soil sample or specific components for comparison. For forensic investigations the robustness and the potential evidential value of such comparisons can be increased by using multiple methods. Combining results from different methods in one forensic evaluation can, however, be difficult.

An example of a successful combination of methods for forensic soil traces is the analysis of bacterial DNA and elemental composition [1,2]. Bacterial DNA composition depends on the local bacterial flora and can change over short distances due to differences in soil moisture, chemical and organic components, or vegetation. The elemental composition depends on the local geology and human contamination and usually changes over larger distances. Thus, if a soil trace from a questioned item is similar, in both bacterial DNA and elemental composition, to a soil sample from a location, these results are “convergent” pieces of evidence [3] that support the same proposition. The only question is to what extent. However, if the bacterial DNA results show large differences and the elemental composition shows substantial similarities between samples, the results are “divergent” pieces of evidence [3] that support different propositions. The question is which proposition is supported by the combination, and to what extent. Thus the interpretation becomes more complicated.

During the interpretation of the results of casework these difficulties are evaluated and taken into account using expert opinion, imposing the risk of cognitive bias on results obtained by strict guidelines and with minimal subjective factors. As more methods are used to compare the same samples, the interpretation becomes more complex and the reasoning leading to the final conclusion can become unclear.

Publications on forensic soil comparisons have shown different approaches to interpret and report results, which can be categorized as exclusionary, stating comparability, or using propositions [4]. Exclusionary reporting is advised by forensic soil scientists from the United Kingdom [5] while stating comparability is favoured by forensic soil scientists from Australia [6]. Reporting using propositions applies the Bayesian framework to assess how strongly the evidence supports one proposition over the other and is advised by both UK [7] and European [8] forensic organizations to assist in interpretation and promote transparency.

In the Bayesian framework results are evaluated by considering two mutually exclusive propositions (or hypotheses) that, in addition, are often exhaustive (i.e. covering all possibilities under the circumstances of the case) [7]. Usually the proposition of the prosecution (Hp) and of

* Corresponding author at: Netherlands Forensic Institute, P.O. Box 24044, 2490 AA The Hague, The Netherlands.
E-mail address: s.uitdehaag@nfi.nl (S.C.A. Uitdehaag).

https://doi.org/10.1016/j.scijus.2022.02.005
Received 8 July 2021; Received in revised form 21 January 2022; Accepted 13 February 2022
Available online 16 February 2022

the defence (Hd) are considered. Furthermore, we consider information (I) about the context of the case. This information is taken as known to us throughout this paper, but for sake of readability, we omit "given that we know I" in all probabilities below. Bayes' theorem shows how evidence changes the probabilities of these propositions according to:

$$\text{Prior odds} \times \text{likelihood ratio} = \text{posterior odds}.$$

The prior odds are the odds of the proposition Hp being true *before* the evidence is considered. The likelihood ratio (LR) is the ratio between the probability of finding the evidence if Hp is true and the probability of finding the evidence if Hd is true. The posterior odds are the odds of the proposition Hp being true *after* the evidence is considered. In case the two propositions do not describe all possibilities (i.e. are not exhaustive), the odds are defined as the ratio of the probabilities of Hp being true and of Hd being true.

The assignment of the prior odds is delegated to the court, because this is typically outside the scientist's field of expertise and therefore scientists do not have procedural legitimacy. The court has access to all the information of the case and can also prevent the same information from being used multiple times. Within this framework the forensic scientists report a LR (the evidential value) for two propositions to the court who can then update their prior odds to their posterior odds. Note that the LR concerns the probability of the evidence given a proposition, not vice versa.

The propositions are generally categorized using the hierarchy of propositions [9] at (sub)source, activity, or offence level, whereby the offence level is generally less suited for evaluation by forensic scientists. Source level propositions are propositions that consider whether samples share the same (specific) source regardless of circumstances. Due to practical limitations it's not feasible in forensic soil comparisons to analyse sufficient samples to provide a robust distribution of characteristics within the alleged specific source. Instead, the comparisons consider a common source (see [10] for more information on the common and specific source comparisons). Regardless, these source level propositions are the types usually considered in forensic soil comparison studies. Activity level propositions also consider the case circumstances and activities that produced the samples such as smashing a window or digging a grave. Publications on activity level propositions for forensic soil casework are however scarce. Activity level propositions have become increasingly important in forensic science in general, but are also more complex to evaluate results given these propositions [11,12,13].

When the results of different methods are evaluated using the same propositions, a Bayesian network (BN) can be helpful to identify and quantify the different factors that can affect the evidential value. A BN is a graphical representation of all these different factors and their dependencies combined with a tool for the probabilistic analysis. The forensic literature shows a steady increase in BN application areas, ranging from human DNA [14], glass fragments [15] to blood alcohol concentrations [16] but for forensic soil analysis BNs have not yet been published.

For an introduction into creating and applying BNs the studies Dawid and Evett [17], Charniak [18] and Taroni et al. [19] provide a good starting point. In summary, a BN consists of different nodes (usually drawn as circles) connected by directed links (usually drawn as arrows). The different nodes can represent the propositions, questioned activities, factors of influence or results from analyses. Every node can be given several states (e.g. yes/no or sand/clay/organic). The arrows represent the dependencies of the nodes on each other.

The influencing nodes are referred to as parent nodes and the nodes they influence are referred to as child nodes. A single node can have both roles, but they must influence different nodes. Every node with one or more parent nodes (i.e. a child node) has a conditional probability table consisting of a number of columns (i.e. the conditions) equal to all the state combinations of all the parent nodes of the child node and a number of rows equal to the number of states defined for the child node (see e.g. Table 1). Nodes without parent nodes are termed root nodes and their table consists of a single column describing the prior probabilities of each state. For all child nodes probabilities have to be assigned to each cell in their table. These probabilities are conditional: we specify the probability of observing the row state, given that the columns states are true. For example, when the *'sediment at the crime scene'* parent node has an arrow pointing to the *'transfer of soil'* child node, we can assign a larger transfer probability to *'clay'* (e.g. 80% when wet) than to *'sand'* (e.g. 20% when wet) expressing the dependence of transfer on sediment type and moisture (see Table 1). Note that a missing value or cumulative zero probability for an entire column breaks the calculation tool, so even when a column is irrelevant or impossible, a "dummy" value should be assigned (e.g. all ones). These "dummy" values will not affect the other nodes in the network if the column is truly irrelevant.

A template has been published to construct BNs in forensic human DNA cases [20] that can be adapted to other forensic fields. However, when compared to forensic human DNA, there is a lack of published data on transfer, persistence, recovery, and background for forensic soil comparisons, so expert opinion has to be used to assign probabilities to the majority of the nodes.

The use of a BN will not improve the quality or quantity of the data but forces the expert to explicitly define propositions, findings, and dependencies, and to quantify all relevant probabilities. Currently, the expert uses all (or most) of these to form a conclusion too, but much more implicitly. Hence, it is expected that the use of a BN will improve the transparency of the expert's reasoning and assist in structuring it.

This study introduces and explores the use of BNs in forensic soil analysis. We provide two examples of a BN for evaluating results of soil comparison: the first example using source level propositions and the second example with activity level propositions. The probabilities assigned to the different nodes were chosen to be realistic but are mainly provided as an example. In casework, a sensitivity analysis is important to ensure that the conclusion is robust. The BN allows to calculate a LR, but its value should be interpreted as a rough order of magnitude rather than a precise number. The examples can be used by forensic soil experts to explore the benefits and drawbacks of using a BN and provide two starting points to construct their own BN for their casework.

2. Construction of two example Bayesian networks

Taylor et al. [20] provides a practical approach to construct a BN for evaluating results given activity level propositions in forensic biology considering several difficulties the forensic practitioner regularly encounters, such as the lack of a template, time pressure in a forensic lab and problems with constructing a BN before results are obtained. In their approach seven steps are described to define nodes, which are assigned standard colours and are linked in a BN. The resulting BN is not only used for calculating evidential value, but is also meant to explain the expert evaluation to others.

Biedermann et al. [21] considers activity level propositions to interpret evidence on the number of recovered gunshot residue particles. This paper also describes how to support case pre-assessment [22]

Table 1
Example probability table for *'transfer of soil'* child node with two parent nodes. Node 1 and Node 2 are two parent nodes, *'sediment at CS'* and *'moisture at CS'* with two states each: clay & sand and wet & dry respectively. The *'transfer of soil'* child node has three states. Probabilities (percentages) are entered into the 12 fields, whereby every column sums up to 100 percent.

Node 1 sediment at CS	clay		sand	
Node 2 moisture at CS	wet	dry	wet	dry
State 1 no transfer	0%	75%	20%	95%
State 2 small amount	20%	25%	60%	5%
State 3 large amount	80%	0%	20%	0%

through a BN. The modelling approach and level of mathematical detail in these two papers is quite different. Taylor et al. [20] model various activities in separate nodes, and in their worked example combine the transfer, persistence, and recovery of DNA without considering the number of cells. Thus they rather roughly model the different routes by which DNA is transferred to certain items and combine different types of DNA test results. Biedermann et al. [21] focus on a single activity and a single test result, and model the number of particles that transfers, persists and is recovered in separate nodes and in a detailed way.

For this study we adapted the procedure from Taylor et al. [20] to forensic soil comparisons using the same colour scheme. The software Hugin Expert version 8.6 (www.hugin.com) was used for the construction of the BNs and contains the necessary calculation tools.

The steps for constructing a BN for forensic soil comparison using source level propositions are: Step 1: Define the two propositions and construct starting nodes (black), Step 2: Define findings nodes (red), Step 3: Define root nodes (grey), Step 4: Assign probabilities, Step 5: Check for absolute support. These steps will be further explained during the construction of the example. The final BN is shown in Fig. 1. Additional steps will be added to construct a BN for forensic soil comparison with activity level propositions, where factors such as transfer and persistence have an impact on the findings [8].

2.1. Source level example

2.1.1. Step 1 Define the two propositions and construct starting nodes

In this step the two propositions, generally Hp (prosecutor) and Hd (defence), are defined and added to the BN (top of Fig. 1). The two propositions under consideration must not overlap (i.e. be mutually exclusive), so only one of them can be true at any time. It is commonly advised not to formulate one of the propositions as a negation of the other, making it more transparent to the reader what situations are covered [24]. Some authors ([25] for example) state that the two propositions should be exhaustive (i.e. cover all possibilities), but in soil comparison casework this generally does not fit the relevant questions of the trier of fact. By specifying the assumptions used in the BN this gap can be addressed. Assumptions can be saved in the network description or can be visualized in the graph by adding a loose 'dummy' node (as shown in Fig. 1).

For the example BN with source level soil comparison we use the following fictional case description. The questioned soil trace has been

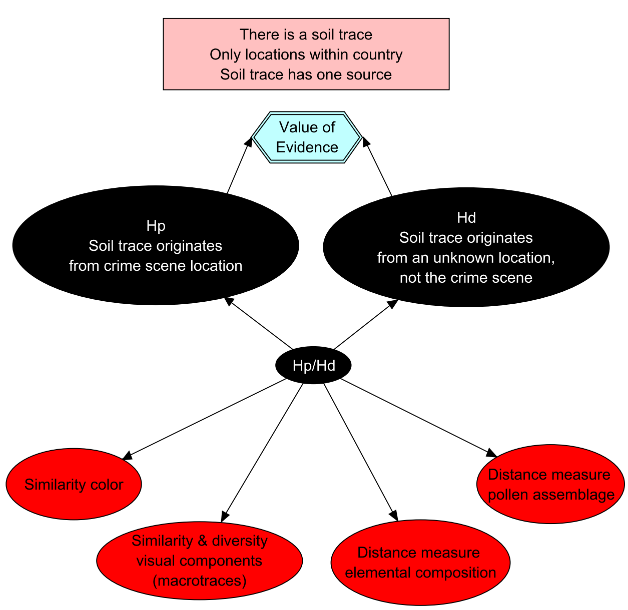

Fig. 1. Example of a completed source level soil comparison BN.

obtained from the shoe of the suspect. The location of interest is the crime scene and the question is whether the trace originates from this location. We compare the single soil trace to a single sample from the crime scene using several analytical methods. After constructing a BN for this case we will discuss how it can be extended to more realistic situations with multiple questioned samples or reference samples or both.

The two propositions on the source of the questioned soil trace found are formulated as:

Hp: The questioned soil trace originates from the crime scene location.

Hd: The questioned soil trace originates from an unknown location, not the crime scene, within the country.

For these propositions the term 'location' should be defined (see [1] for a discussion on defining location) in a consistent manner that preferably is the same definition that the used methods are validated for. For this example, we define the location as an area of roughly 50 m diameter with similar vegetation, soil composition and (historical) land use. This means that locations can vary in size, for example a homogenous agricultural field will be divided in 50 m diameter locations, but an urban area with different patches of soil composition (e.g. construction sand) and gardens will be divided in many smaller locations with similar soil.

The basic assumptions for this BN are that 1) there is a questioned soil trace, 2) locations outside the country are not considered, 3) the questioned soil trace has only one (main) source. In case of soil mixtures only the major contributor is considered, so both propositions cannot be true at the same time. Depending on the propositions in a specific case, the number of necessary assumptions and definitions can vary and must be provided by the forensic practitioner to inform the reader of the scope of the BN.

For the nodes with the propositions "*discrete chance nodes*" are used and the corresponding conditional probability tables are filled with A) an equal probability for both propositions, which provides an equal prior for the 'Hp/Hd' node, and B) values that ensure only the corresponding proposition can be true in the Hp and Hd nodes, i.e. ones and zeroes. The *'value of evidence'* function node calculates the resulting LR value directly from the proposition nodes by dividing the (posterior) probabilities of Hp by Hd starting with an equal prior, so that numbers higher than 1 represent support for Hp and numbers lower than 1 represent support for Hd. This is a general set-up where the *'value of evidence'* node of the BN calculates a LR.

2.1.2. Step 2: Define findings nodes (red)

The methods used for the comparison of one questioned soil trace with one sample from the crime scene location are added using red findings nodes and placed below the nodes from step one. For the BN only methods that can provide results that help distinguish between the two propositions are relevant, but as many findings nodes can be added as necessary. The range of possible results of the different soil comparison methods will be added in the corresponding probability tables in step four.

For this example we added the nodes *'Similarity colour', 'Similarity visual components (macro traces)', 'Distance measure elemental composition',* and *'Distance measure pollen assemblage'* as these are the methods we regularly use for forensic soil comparison (see step 4 for more information).

2.1.3. Step 3: Define root nodes (grey)

Root nodes represent factors that have no direct connection to the propositions considered, but have an influence on the nodes that are present. For example, a certain amount of unrelated soil (background) on a shoe can interfere with the results of the soil comparison of the soil trace from the shoe with samples from the crime scene, so a grey *'background'* node could be added if relevant. Note, that under the assumption that there is only one major source of the soil, the background level can't be too high or the source is no longer the major contributor and the assumption is no longer valid. In this situation, when mixtures are relevant, source level networks concerning a single source are no longer a good option. After adding the grey root nodes the different states of the node must be named, for instance *'low'* or *'high'* for the *'background'* node and defined. In this example of a source level BN (Fig. 1) root nodes are not added, but examples are included in the activity level BN (Fig. 2).

Finally, the '*Hp/Hd*' node can be linked to the findings nodes. In Fig. 1 all findings nodes have a direct single link with the propositions node. This structure implies the assumption that all findings are statistically independent (given that Hp is true, or that Hd is true). As a result, the LR of the combined findings are calculated as a simple multiplication of the LR of each finding separately. If this assumption is thought to be overly simplistic, dependencies can be introduced by adding links between the findings nodes, or by introducing additional nodes representing factors that affect multiple findings nodes. Since the goal of this study is to introduce the concept of a BN to forensic soil scientists, we chose to keep our network as simple as possible.

2.1.4. Step 4: Assign probabilities

After finishing connecting the nodes with relevant links, the underlying conditional probability tables must be filled with probabilities. Assigning proper probabilities is arguably the most difficult part of constructing a BN. For every node different states can be defined, so for instance a *'similarity colour'* findings node can be given two states, such as high or low similarity, or 10 states when there are 10 possible results of the colour comparison.

For source level soil comparisons the soil trace from the questioned item is usually compared only to reference soil samples from the crime scene, as an alternative location is often not provided by the suspect. Therefore, the probability tables must be completed with the possible results of this comparison in mind. At this step only the red findings nodes require values on probabilities, which means that for all the possible results of a specific method (in one findings node) the probability of that result under the columns Hp and Hd (the states of the node with the arrow pointing towards the findings node) must be provided (e.g. Table 2). In casework, the probabilities concern a specific location ("the" crime scene). Here, we use data for "a" crime scene (a nonspecific location).

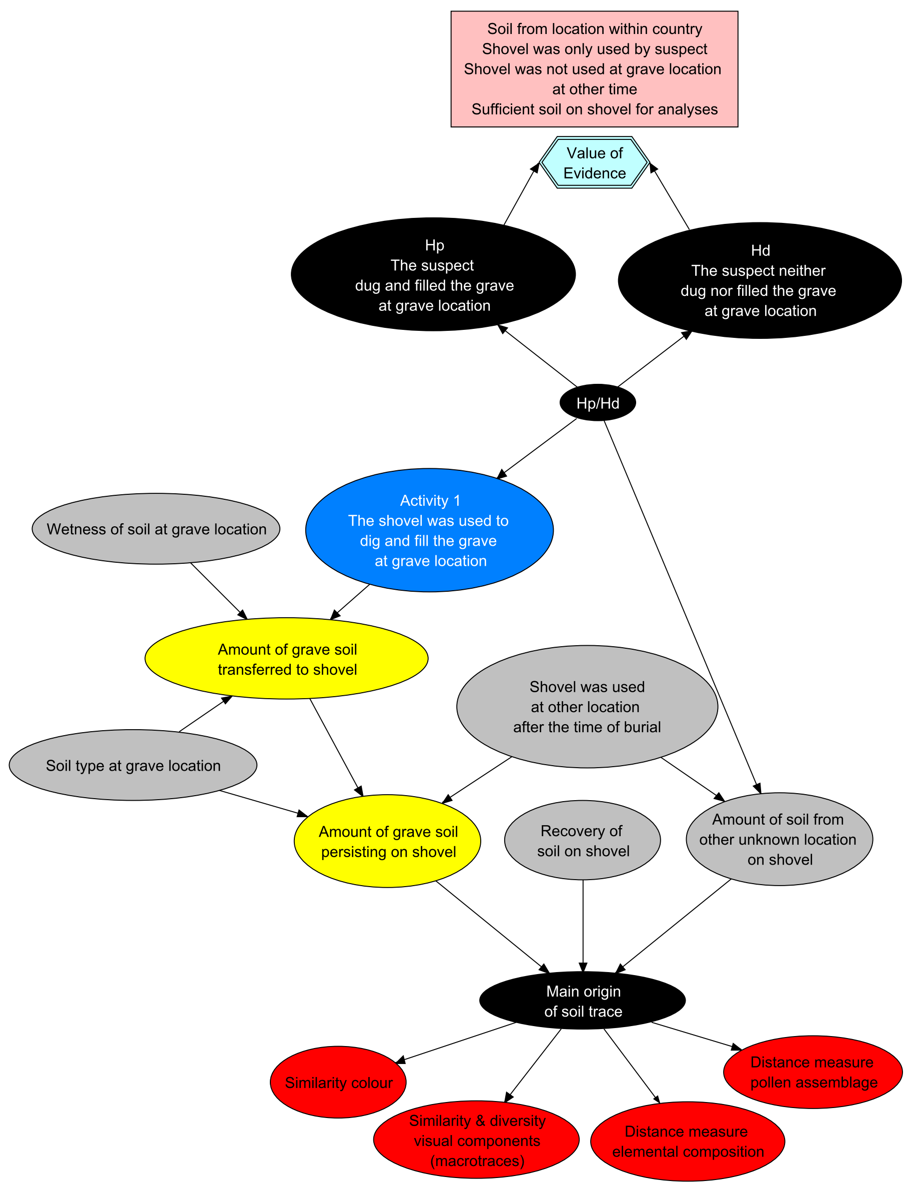

Fig. 2. Example of complete activity level soil comparison BN.

Table 2
Probability table for *'Similarity colour'* node.

Hp/Hd	Hp	Hd
Strong similarity	70%	20%
Weak similarity	28%	30%
No similarity	2%	50%

The consequences of using a specific or a nonspecific location are discussed in Ommen and Saunders [10]. They note that different populations will be chosen to compare with the case samples and a different forensic question will be answered. The probabilities in the tables of the nodes are preferably derived from studies, but expert opinion can be used if necessary.

As the propositions Hp and Hd consider differences *between locations,* the assigned probabilities of the findings must reflect that specific level of spatial resolution. Vice versa, if the propositions are considering differences *between sampling spots,* the assigned probabilities in the finding nodes must be adapted to this spatial resolution. For instance, data of differences between soil samples within a few meters of each other is not informative for propositions that consider differences in kilometers. A consistent definition of a location is also required for the different methods of soil comparison used in the BN.

As there can be multiple samples from the location of the crime scene, there can also be multiple comparisons between those samples and the questioned soil trace. For the example BN in Fig. 1 we consider only a single comparison between a questioned soil sample and one crime scene sample. When multiple samples from the crime scene are available, the relevant question concerns their joint evidential value. The optimal way to derive this is to model this in the BN, but adding this would make the BN very complex and case-specific and is beyond the scope of this study. As a sub-optimal alternative, we use the BN repeatedly for each comparison. In effect, each single comparison is evaluated to see how it fits with the same location proposition, providing a LR for each comparison. To combine and report these results they still have to be evaluated using for instance expert opinion, which would provide an evidential value for the comparison with the location as a whole.

Probabilities assigned in the example below of a working source-level BN are based on our experience or on studies where possible. These probabilities are meant as an example only. When using the example BN as a starting point in casework we suggest assigning probabilities for the specific location based on relevant studies, applied methods and experience. Also the dependency structure may need to be adapted by including additional links. Finally, the specific circumstances of the case may require the introduction of additional nodes such as '*background soil*' or *'weather conditions'*.

For the node *'Similarity colour'* we defined three states of strong, weak and no similarity in colour between the soil trace from the questioned item and one of the reference samples of the crime scene. We assigned values of 70%, 28% and 2% in the Hp column and values of 20%, 30% and 50% in the Hd column to the three states, respectively (Table 2). This translates to expecting a strong, weak, or no similarity in colour in respectively 70%, 28% and 2% of the time when comparing the soil trace to a soil sample from the crime scene, when that soil trace originates from the crime scene. Assigning 2% to the *'no similarity'* result aims to include factors such as non-representative sampling, preferential loss of soil components and other factors that introduce differences and result in false negatives.

And, vice versa, we expect a strong, weak and no similarity in colour in respectively 20%, 30% and 50% of the time when comparing a soil sample from the crime scene to a soil trace from an unknown location (not the crime scene). The relative high percentages for strong and weak similarity for samples from different sources represents the limited diversity of colours in the soils in this country. By dividing these probabilities in each row, the LRs for the possible results of this method and these propositions can be calculated; in this case 3.5, 0.93 and 0.04 respectively.

The numbers in Table 2 and the definition of the degree of similarity are thus based on expert opinion. The level of objectivity can be increased when relevant data become available.

For the node *'Similarity & diversity visual components (macro traces)'* we defined four states: 1) *'strong similarity and high diversity',* 2) *'weak similarity and high diversity',* 3) *'strong similarity and low diversity'* and 4) *'weak similarity and low diversity*'. In this node we consider various larger components such as pine needles, seeds, leaf fragments, plastic pieces and glass fragments. Larger particles in the soil matrix, such as macro traces, generally have a low probability of being part of a small soil sample and tend to dislodge during the use of a piece of evidence, so even when soil samples are from the same source we expect a low probability of both high diversity and strong similarity. We assigned to the Hp column the values of 10%, 40%, 40% and 10% and to the Hd column the values of 1%, 40%, 40% and 19% respectively (Table 3). When specific methods are used for one of these macro traces, e.g. DNA comparison using seeds, these results should be considered in a separate '*findings*' node. In addition, the absence of specific macro traces that are very common in soil traces from a certain geographical region could also have an evidential value [26]. In theory each type of macro trace can be given their own '*findings*' node, but given the huge diversity of macro traces this could make the BN unwieldy. Therefore, adding nodes for specific macro traces should be limited to the most relevant ones. The remaining macro traces are then included in the general *'Similarity & diversity visual components (macro traces)'* node.

For the *'Distance measure elemental composition'* node we use data from an in-house EDXRF comparison method (Table 4). The method is similar to the method described in [1] using the Canberra distance measure on square-root transformed relative quantitative data of 20 elements. For this node, data from the *'same sample spot'* are ignored and only statistical distances between samples from the *'same location'* and '*different locations'* are used, to fit the propositions under Hp and Hd in this BN. As the diversity within locations is greater than within sample spots, this moves the distribution in the direction of the *'different locations'* group and creates more overlap between the two groups. The distance data based on comparison of different locations is used for the proposition under Hd. In addition, more data was added to the database since publication.

Similarly, for the *'Distance measure pollen assemblage'* node we use the data from Uitdehaag et al. [23] where the squared chord metric is calculated between relative data of pollen assemblages with 74 pollen types. The percentage of observations for soil samples from the same location and from a different location are used for the probabilities for Hp and Hd respectively (Table 5).

2.1.5. Step 5: Check for absolute support

Absolute support can occur when a specific result can only occur under one of the two propositions. In the examples of the tables above, all probabilities for both propositions were given values above zero, so no absolute support is given under any result. Note that soil comparisons at source level can produce results that can exclude a location as a source (for example finding red soil on a shoe when there is only black soil at the crime scene). When provided with such obvious exclusionary results, i.e. absolute support, evaluating these results with a source level BN provides no additional information, so adding these results to the nodes

Table 3
Probability table for *'Similarity & diversity visual components (macro traces)'* node.

Hp/Hd	Hp	Hd
Strong similarity and high diversity	10%	1%
Weak similarity and high diversity	40%	40%
Strong similarity and low diversity	40%	40%
Weak similarity and low diversity	10%	19%

Table 4
Probability table for the *'Distance measure elemental composition'* node. The states of this node are given by the intervals of the distance measure calculated between soil trace and a soil sample. The probabilities in the Hp-column are the percentages for samples from the same location (N = 1285). The probabilities in the Hd-column are the percentages for samples from different locations (N = 12645). Values of zero are replaced by 1/n (* = 1/1285, ** = 1/12645) as a value of zero would give absolute support for the other proposition (see step 5). To keep the sum at 100% these replaced values were subtracted from the highest value (§).

Hp/Hd	Hp	Hd
0.5 and lower	20.23%	0.008%**
>0.5–0.7	21.72%§	0.08%
>0.7–0.9	20.39%	0.55%
>0.9–1.1	15.56%	1.34%
>1.1–1.3	9.18%	1.62%
>1.3–1.5	3.11%	3.02%
>1.5–1.7	2.80%	6.20%
>1.7–1.9	4.20%	7.85%
>1.9–2.1	2.57%	7.21%
>2.1–2.3	0.16%	6.82%
Higher than 2.3	0.08%*	65.30%§

Table 5
Probability table for the *'Distance measure pollen assemblage'* node. The states of this node are given by the intervals of the distance measure calculated between two pollen assemblages. The probabilities in the Hp-column are the percentages of observations of samples from the same location (N = 63). The probabilities in the Hd-column are the percentages for samples from different locations (N = 1712). Rounding errors are subtracted from the highest value (§) to keep the sum at 100%.

Hp/Hd	Hp	Hd
0.155 and lower	39%§	0.1%
>0.155–0.231	37%	1%
>0.231–0.307	11%	3%
>0.307–0.383	6%	4%
>0.383–0.459	3%	7%
>0.459–0.535	2%	9%
Higher than 0.535	2%	75.9%§

provides no benefit.

The results of different methods to compare one questioned soil trace to one sample from the crime scene location can be selected (instantiated) in the red findings nodes. The resulting combined evidential value for the propositions in the black nodes is then calculated in the light blue node. Assumptions made for the entire BN are in the box above.

At this point a working example of a BN for source level forensic soil comparisons is constructed. By instantiating (selecting) the different results of the methods in the '*findings*' nodes, the evidential value of the combined results, assuming conditional independence, is calculated by this BN. This value varies between 1.3×10^{-6} and 3.5×10^{8} and is therefore able to provide support to both propositions (i.e. the LR can be both higher and lower than one). The evidential value depends on what probabilities are entered into the different tables and will be different when other probabilities are considered for a specific case or because databases are expanded. As the probabilities in the tables and the dependencies are clearly defined in the BN, these can now be debated and updated between experts.

2.2. Activity level example

For the activity level example shown in Fig. 2 we will expand the source level example and add nodes that express the difficulties that are often relevant when evaluating results for casework at this level. For this example we will keep the nodes general, so it is applicable to a wider variety of cases. As many cases share similar parts the example BN can be easily adapted to the case at hand.

The steps for evaluating activity level propositions are (based on [20]): Step 1: Define the two propositions and construct starting nodes (black), Step 2: Define activity nodes (blue), Step 3: Define findings nodes (red), Step 4: Define transfer and persistence nodes (yellow), Step 5: Define root nodes (grey), Step 6: Assign probabilities, Step 7: Check for absolute support.

2.2.1. Step 1: Define the two propositions and construct starting nodes (black)

Propositions on activity level can be as open as *'the suspect was present at the crime scene'* or more specific as for example *'the suspect was walking at the crime scene'* or even *'the suspect dug the grave at the crime scene'*. In general, activity level propositions should describe an activity but not cross over into offence level, the next level of the hierarchy of propositions. However, some offence level propositions such as *'the suspect (illegally) buried the victim at the crime scene'* can be very close to activity level propositions such as *'the suspect dug and filled the grave at the crime scene'*, so it is advisable to check with the parties involved what propositions to use.

For this example we use the following fictional case scenario. A body of a woman was found buried in the forest floor near a dirt road. The ex-boyfriend of the victim was arrested a few days later and his shovel was secured. The prosecutor has the following scenario: The suspect drove his car with the dead victim in the trunk to the crime scene and dragged the body to the location where he then proceeded to bury her. During preliminary forensic investigation soil traces on the shovel were found. The prosecutor requests an investigation to find out if the suspect used the shovel at the location of the grave and provides the following proposition:

Hp: *The suspect dug and filled the grave at grave location.*

The suspect states that he never was at that location. He states that he does not know where the soil on his shovel comes from, but it was used regularly. This is summarized in the defence proposition:

Hd: *The suspect neither dug nor filled the grave at grave location.*

Note that both propositions do not specify the time and implicitly assume that no other graves (or holes) were dug at this location with this shovel within the relevant timeframe. For this case we also assume that the shovel has not been used by someone else. This assumption is possible as long as the suspect does not claim otherwise and can be considered "undisputed case information" [24]. We also assume that the soil trace on the shovel originates from within the country as there is no indication that areas outside the country are relevant and is appropriate for the data in the findings nodes (when a larger area is considered then other data must be used in these nodes).

2.2.2. Step 2: Define activity nodes (blue)

In these nodes activities are defined, given the propositions from prosecution and defence, that influence the soil comparison. For the given scenario there is only one questioned activity *'the shovel was used to dig and fill the grave at grave location'*. For this node we defined the states as true and false. Note that if the suspect claimed that the shovel was used at another specific place this can be added as the alternative activity.

In addition, activities that are not disputed but may impact forensic results can also be added as activity nodes. We add a node *'shovel used at other location after the time of burial'* to the example BN to represent possible use of the shovel, not related to the main propositions but relevant to the interpretation, and defined the states *'yes'* and *'no'*.

2.2.3. Step 3: Define findings nodes (red)

The findings nodes are the same as for the source level BN. We connect all these nodes to a black node *'main origin of soil trace'*, which contains the combined result of all the findings on source level. We defined two states for this black node *'Alleged-source'* and *'Unknown-source'*, which represent a common origin of the soil trace with one reference sample of the location where the victim was found buried and no common origin (i.e. an unknown alternative location as origin), respectively.

2.2.4. Step 4: Define transfer and persistence nodes (yellow)

These nodes define the mechanisms between the activities and the possible findings. We include a transfer node *'amount of grave soil transferred to shovel'* with the states *'large amount'*, *'medium amount'* and *'small to zero amount'*. We also include a persistence node *'amount of grave soil persisting on shovel'*, since the shovel was seized after some time had passed since the alleged activity took place. For this node the same states are defined. For these states both *'large'* and *'medium amount'* are defined as sufficient material for a soil comparison and *'small to zero amount'* is defined as less material or no material.

As some methods need less material for a valid comparison than others, and so are differently affected by the amount of material that persists, the states can also be defined as for instance *'1 to 2 g of material'* or *'less than 1 g of material'* as long as these states do not overlap. When more than one location is considered (multiple activities) every location requires their own transfer and persistence nodes. After constructing all yellow nodes in the BN the relevant activity nodes are then connected to their relevant transfer nodes. The transfer nodes can then be connected to their relevant persistence nodes.

The example BN is constructed with the assumption that there is soil present on the shovel, so if the soil is not from the grave location, it must be from another, unknown, location. This is represented by the *'amount of soil from other unknown location'* node with the same states *'large amount'*, *'medium amount'* and *'small amount'*. This node is then connected to the *'Hp/Hd'* node and the *'main origin of soil trace'* node. And finally, as the persistence of soil traces from the crime scene and the transfer/persistence of soil traces from the other unknown location are both influenced by later use, we connect the *'shovel used at other location after the time of burial'* node both to the *'amount of grave soil persisting on shovel'* node and the *'amount of soil from other unknown location'* node.

2.2.5. Step 5: Define root nodes (grey)

There are many factors that influence soil comparisons which are not related to the activities under consideration and these can be included as grey nodes. For this example we consider that the transfer of soil from the location of the grave to the shovel is influenced by the moisture content of the soil in the relevant time period and the soil type. We define the states *'relatively wet'* and *'relatively dry'* to the *'wetness of soil at grave location'* node. For the *'soil type at grave location'* node we define the states *'sand'*, *'clay'* and *'organic'*, which describes the prevalent soil type states in the region stated in the propositions. These nodes are connected to the transfer node of the grave site. Soil type also has an influence on persistence, so this node is also connected to the persistence node.

For this example BN we consider that the recovery of the soil on the shovel in the lab has two possible results: 1) one or more soil traces on the shovel could be distinguished and have been recovered as separate soil traces so that they, or at least the main contributor per trace, can be compared to other samples, 2) different soil traces could not be distinguished completely, recovery has possibly introduced additional minor contributors to the traces, but the traces are still suitable for comparison. In theory there is a third result when the recovery of a suitable (unmixed) soil trace is not possible even though there is enough (mixed) soil present (see assumptions). In this example BN this result would make the entire BN obsolete as a valid soil comparison is no longer possible, so it was not included. In practice the expert should evaluate the recovery before analyses are run to prevent unnecessary work and possible bias. We define for the *'recovery of soil on shovel'* node the states *'good recovery'* and *'possible mixing'* and connect it to the *'main origin of soil trace'* node.

2.2.6. Step 6 Assigning probabilities

After connecting all the nodes (Fig. 2) values can be assigned to all the conditional probability tables. In the example activity level BN the lower black proposition nodes, the evidential value node and all the red finding nodes have the same tables as used in the example source level BN provided above. Additional values have to be assigned to all other nodes.

Starting with the activity nodes, *'the shovel was used to dig and fill the grave at grave location'* node has two states '*true*' and '*false*' and one '*Hp/Hd*' node that influences it. For the Hp-proposition the probability that this specific shovel was used if Hp is true should be given. This probability is heavily influenced by case circumstances, such as the number of shovels available to the suspect and the chance that the actual shovel used is still hidden or was destroyed. For this example BN the probabilities were set at 100% true and 0% false, in effect stating that no other shovels are considered. For casework these probabilities should be revisited for each case. For the Hd proposition the probabilities were set at 0% true and 100% false. The *'shovel used at other location after the time of burial'* node is a root node and the two states were set at equal probability.

The *'amount of grave soil transferred to shovel'* node has three states and three nodes with in total twelve states that influence it. The assigned probabilities are given in Table 6. The probabilities are based on estimates of transfer rates. They would be improved by relevant transfer studies and can also be affected by the surface texture of the shovel (e.g. rusted versus new). In general we assign higher transfer rates to clay than organic, which in turn is higher than sand, and relatively wet soil increases transfer compared to dry soil. In addition, when the questioned activity is not true there is no transfer (i.e. zero amount) from the grave location.

The *'amount of grave soil persisting on shovel'* node has three states and three nodes with in total eighteen states that influence it. The assigned probabilities are given in Table 7. The probability of a similar amount of material persisting after transfer is higher for soil types with higher persistence. Clay is given a higher persistence than organic with the lowest persistence given to sand. For instance, when a medium amount of soil was transferred and the shovel was not used at another location afterwards and the soil type is clay, we assign a 95% probability that a medium amount of clay will remain and a 5% probability that only a small or zero amount will remain.

The *'amount of soil from other unknown location'* node has three states and two nodes with in total four states that influence it. The assigned probabilities are given in Table 8. For instance, we assign an 80% probability that a medium amount of soil will be present when the defence proposition is true or when the shovel was used at another location after the burial. This node includes the general background amount of soil on random shovels unrelated to crime scene.

The *'main origin of soil trace'* node has two states and three nodes with in total eighteen states that influence it. The assigned probabilities are given in Table 9. Note that if almost no soil of the crime scene remains on the shovel due to unfavourable transfer and persistence, the source of the soil trace that is present on the shovel must be from another unknown location.

2.2.7. Step 7: Check for absolute support

With values assigned to all the tables, the BN can be checked for absolute support by instantiating the red nodes and the grey root nodes (nodes without parents) to see if one of the propositions is excluded. The example BN does not provide absolute support for one of the propositions, so can be used for further analyses. When evaluating findings under two propositions with a BN, when the assumptions are not valid or both propositions are not exhaustive, in theory both propositions could be false and the BN will not provide meaningful values under these circumstances [27,28].

The constructed BN can now be tested to see the effect the grey root (without arrows towards them) nodes have on the evidential value. For example, setting the findings at the highest similarity and switching between the different options of the grey root nodes provides a value of

Table 6
Probability table for the *'amount of grave soil transferred to shovel'* node. Activity 1 is the questioned activity 'the shovel was used to dig and fill the grave at grave location'. Wetness is the soil humidity at the crime scene. Soil type is the type of soil at the crime scene.

Activity 1	False						True					
Wetness	Relatively wet			Relatively dry			Relatively wet			Relatively dry		
Soil type	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.
Large amount	0%	0%	0%	0%	0%	0%	10%	75%	25%	0%	20%	10%
Medium amount	0%	0%	0%	0%	0%	0%	85%	25%	75%	20%	40%	40%
Small or zero amount	100%	100%	100%	100%	100%	100%	5%	0%	0%	80%	40%	50%

Table 7
Probability table for the *'amount of grave soil persisting on shovel'* node. Transfer is the amount of soil transferred from the crime scene to the shovel. Use shovel is an activity where the shovel was used at another unknown location after the time of burial. Soil type is the type of soil at the crime scene.

Transfer	Large amount						Medium amount						Small to zero amount					
Use shovel	Yes			No			Yes			No			Yes			No		
Soil type	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.	Sand	Clay	Org.
Large amount	0%	10%	10%	20%	90%	90%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Medium amount	10%	90%	90%	70%	10%	10%	10%	50%	30%	70%	95%	90%	0%	0%	0%	0%	0%	0%
Small or zero amount	90%	0%	0%	10%	0%	0%	90%	50%	70%	30%	5%	10%	100%	100%	100%	100%	100%	100%

Table 8
Probability table for the *'amount of soil from other unknown location'* node. Hp/Hd are the two propositions, prosecution and defence, under consideration in the BN. 'Use shovel' is an activity where the shovel was used at another unknown location after the time of burial.

Hp/Hd	Hp		Hd	
Use shovel	Yes	No	Yes	No
Large amount	15%	0%	15%	15%
Medium amount	80%	5%	80%	80%
Small or zero amount	5%	95%	5%	5%

evidence between $7x10^6$ and $3x10^8$ in support of Hp. The lowest value is found with the options of '*relatively dry sand on the grave location*', '*possible mixing during sampling*' and '*use of the shovel after the burial*'. These options represent circumstances that, if the shovel was used at the grave location, most of the soil trace of the grave location is expected to be lost from the shovel or possibly mixed with soil from another location. In contrast, the highest value is found with the options '*relatively wet clay on the grave location*', '*good separation during recovery*' and '*no use of the shovel after the burial*'. These are options that represent ideal circumstances to retain a soil trace from the grave location if the shovel was used there.

Setting the finding nodes at the lowest similarity (highest difference) for all findings, the example BN provides values between $1x10^{-2}$ and 1 in support of Hd. The lowest value (greatest support of Hd) is found under circumstances that are ideal to retain soil traces of the grave location. These are the same circumstances where the maximum value in support of Hp is found when findings are at the other extreme. The highest value (slightly supporting Hd) is found under circumstances that are not ideal for retaining the soil trace and introduce possible mixing. These are the same circumstances where the minimum value in support for Hp is found when findings are at highest similarity.

It is clear that the example BN does not calculate a large support for Hd even when the soil comparison results indicate a different source for the recovered soil trace. This is expected since these same results are also found when most of the soil trace from the grave location was lost during the persistence, transfer and recovery steps, and soil from another unknown location is the remaining major component. Therefore these soil comparison results can be well explained by both propositions, which corresponds to a LR closer to one.

For this example BN the grey *'recovery of soil on shovel'* node, with its effects on the *'main origin of soil trace'* node, has only a small effect on the LR, so this node could be removed from this BN. If included, it shows that the effect has been considered even though it has limited influence. In addition, for research purposes nodes with little effect can be given a lower priority on the agenda. Note that when other values are assigned to the probabilities affected by this node, simulating more mixing or a less effective recovery, the effect would be different.

3. Discussion and conclusion

The two BN examples presented in this study show the differences between evaluating soil evidence at source level and at activity level. For source level comparisons the evidential values can be very high, when conditional independence is assumed, and can be increased further by developing more methods, improving current methods, and enlarging databases.

The findings nodes in the example BN use (dis)similarity scores or values. These do not take into account the rarity of the different components. Intuitively, if more rare components are present in both questioned soil trace and reference soil sample the more valuable the similarity should be. The best way to incorporate rarity is an active area of research [30,31]. There is currently no simple solution to add nodes for rarity when comparing over a hundred different components, as is common in soil comparison, to a BN that includes nodes with similarity values. This is mainly due to unknown co-dependencies that are difficult to weigh properly. In this example BN rarity is therefore not included.

The accuracy of the calculated LR is dependent on how valid the assumptions and the used data are, so the number should be used as an approximation of the order of magnitude of the evidential value. Furthermore, as with any forensic method, a validation study is necessary for actual use in casework.

As shown in the example source level BN, different methods can be incorporated into one BN that is able to calculate the LR for the propositions under consideration. This provides other parties within the court system with an explicit evaluation of the evidence by the forensic practitioner. However, when reporting at source level, factors such as differences in persistence and transfer, possible mixtures and alternative activities are not included in the comparison and should be considered separately. There is a risk that, when only the source level comparison results are reported, these factors are evaluated by other parties within the court system, such as the trier of fact, who are generally less familiar with the complexity of soil analysis. We thus follow the proposition in

Table 9
Probability table for the *'main origin of soil trace'* node. CS remains describes the amount of soil from the crime scene remaining described by the yellow persistence node. Other loc is the amount of soil on the shovel from another unknown location. Recover is the type of recovery of the soil trace from the shovel, G for good recovery with no mixing, P for possible mixing.

CS remains	Large amount						Medium amount						Small to zero amount					
Other loc	Large		Medium		Small		Large		Medium		Small		Large		Medium		Small	
Recover	G	P	G	P	G	P	G	P	G	P	G	P	G	P	G	P	G	P
Alleged-source	100%	95%	100%	99%	100%	100%	100%	90%	100%	95%	100%	99%	0%	0%	0%	0%	0%	0%
Unknown-source	0%	55	0%	1%	0%	0%	0%	10%	0%	5%	0%	1%	100%	100%	100%	100%	100%	100%

Gill et al. [13] for DNA, "*we would like to underline that while sub-source level propositions are of great value for investigation purposes, they do not help to address questions on 'how' the DNA got there or 'why'.*" and want to stress that it is the expert's duty to consider these questions also for soil analysis, and explain the difficulties involved.

Experts are often hesitative to use Bayesian networks because they seem to require a lot more assumptions on probabilities and their dependencies than stating an opinion on the evidential value and describing the arguments verbally. It is important to realize that the latter also requires such assumptions and the same complexity level of reasoning when done properly. The only difference is that the network makes it explicit. The mere construction of a network may be helpful in structuring complex reasoning, regardless of whether the network is subsequently reported to the court.

Going beyond the question of whether a soil trace originates from common single source (i.e. one specific sampling spot) is the question whether it originates from a common location (i.e. multiple samples). A pragmatic solution is to use the example BN to provide the different LRs of all the comparisons of the trace with the crime scene samples and address the combined results during the interpretation step of the forensic report. However, a solution that could be incorporated in the BN would be preferable in order to increase objectivity.

For activity level comparisons, factors such as persistence can be incorporated as shown in the example activity level BN. By changing the values of the probabilities associated with individual nodes, the sensitivity of a target output (the probability of a certain state of a certain node) within the BN to these changes can be evaluated, which might lead to avenues for further investigation. The provided example BN can be expanded if, for instance, different propositions are being considered or different comparison methods are used. Other possible options include the combined evaluation of multiple soil traces on, for instance, shoes and a shovel using the same activity level propositions for all traces, or even combining soil evidence with human DNA evidence to investigate who used a specific item. BNs with multiple types of evidence [29] can also provide the court with better insight in the overall value of all the forensic evidence [10] or the potentially added value of additional forensic investigation.

Activity level BNs are especially useful when both activities in the BN can produce the same findings at the source level, but have different probabilities assigned to the other activity-level nodes. For forensic soil comparison this would include casework where both activities occur on the same location (source) but for instance on different days or with different transfer/persistence probabilities such as walking versus dragging and digging. The evidential value from these types of BNs is mostly influenced by the transfer, persistence and recovery nodes, which means that adding '*findings*' nodes with new soil comparison methods will be less valuable to resolve these questions. For these types of cases additional transfer, persistence and recovery studies add more value than developing new forensic soil comparison methods.

As shown in the example, numerous probabilities have to be assigned to the conditional probability tables when constructing a BN. The probabilities we assigned can therefore be considered as a starting point and can be improved by using additional relevant studies. Although in general such studies are lacking for forensic soil comparison relative to other forensic fields, presenting the example BNs and the underlying probability tables provides a stimulus for more research on these topics. Fortunately, soil traces are visible and relatively large, compared to other forensic traces such as DNA-molecules or single particles, and are commonly encountered in everyday life. For these types of traces, common sense can be helpful to evaluate the given probabilities in the different nodes or can even be explicitly used.

When comparing the use of a BN to the different approaches to reporting forensic soil comparisons, constructing a BN is time consuming but can incorporate many of the complexities of this type of evidence, such as mixed traces, background material and use of multiple methods. However, for forensic soil comparisons using a single method and focusing on source level propositions a BN will not add much value. A common obstacle to using BNs is that building a case specific BN is difficult especially when a proper template is lacking. The two examples of the BNs described in this study have the potential to serve as such templates to support other forensic practitioners in constructing their own BN for evaluating results of forensic soil comparison.

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.

Acknowledgements

The authors are grateful to the anonymous referees for their fruitful comments.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

[1] S. Uitdehaag, W. Wiarda, T. Donders, I. Kuiper, Forensic Comparison of Soil Samples Using Nondestructive Elemental Analysis, J. Forensic Sci. 62 (4) (2017) 861–868.
[2] F.C.A. Quaak, I. Kuiper, Statistical data analysis of bacterial t-RFLP profiles in forensic soil comparisons, Forensic Sci. Int. 210 (1-3) (2011) 96–101, https://doi.org/10.1016/j.forsciint.2011.02.005.
[3] D.A. Schum, A science of evidence: contributions from law and probability, Law Probab. Risk 8 (3) (2009) 197–231, https://doi.org/10.1093/lpr/mgp002.
[4] S.C.A. Uitdehaag, T.H. Donders, I. Kuiper, F. Wagner-Cremer, Challenges in modern forensic palynology, in: Forensic soil comparison: towards objective methods for a more robust evidential value, Utrecht University, Utrecht, 2021, pp. 9-27. https://doi.org/10.33540/652.
[5] R.M. Morgan, P.A. Bull, The philosophy, nature and practice of forensic sediment analysis, Prog. Phys. Geog. 31 (1) (2007) 43–58, https://doi.org/10.1177/0309133307073881.
[6] R.W. Fitzpatrick, M.D. Raven, How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists, Soil Horizons 53 (5) (2012) 14–29, https://doi.org/10.2136/sh12-05-0016.
[7] Association of Forensic Science Providers, Standards for the formulation of evaluative forensic science expert opinion, Sci. Justice 49 (2009) 161-164. https://doi.org/10.1016/j.scijus.2009.07.004.
[8] ENFSI, Guideline for evaluative reporting in forensic science, https://enfsi.eu/wp-content/uploads/2016/09/m1_guideline.pdf, version 3.0, 2015 (accessed 10 December 2020).
[9] R. Cook, I.W. Evett, G. Jackson, P.J. Jones, J.A. Lambert, A hierarchy of propositions: deciding which level to address in casework, Sci. Justice 38 (4) (1998) 231–239, https://doi.org/10.1016/S1355-0306(98)72117-3.
[10] D.M. Ommen, C.P. Saunders, Building a unified statistical framework for the forensic identification of source problems, Law Probab. Risk 17 (2) (2018) 179–197, https://doi.org/10.1093/lpr/mgy008.
[11] F. Taroni, A. Biedermann, S. Bozza, J. Comte, P. Garbolino, Uncertainty about the true source: A note on the likelihood ratio at the activity level, Forensic Science International 220 (1-3) (2012) 173–179.
[12] J.A. de Koeijer, M.J. Sjerps, P. Vergeer, C.E.H. Berger, Combining evidence in complex cases-a practical approach to interdisciplinary casework, Sci. Justice 60 (1) (2020) 20–29, https://doi.org/10.1016/j.scijus.2019.09.001.
[13] P. Gill, T. Hicks, J.M. Butler, E.d. Connolly, L. Gusmão, B. Kokshoorn, N. Morling, R.A.H. van Oorschot, W. Parson, M. Prinz, P.M. Schneider, T. Sijen, D. Taylor, DNA commission of the International society for forensic genetics: Assessing the value of forensic biological evidence-Guidelines highlighting the importance of propositions. Part II: Evaluation of biological traces considering activity level propositions, Forensic Sci. Int.-Gen. 44 (2020) 102186, https://doi.org/10.1016/j.fsigen.2019.102186.
[14] A. Biedermann, F. Taroni, Bayesian networks for evaluating forensic DNA profiling evidence: a review and guide to literature, Forensic Sci, Int.-Gen. 6 (2) (2012) 147–157, https://doi.org/10.1016/j.fsigen.2011.06.009.
[15] G. Zadora, Evaluation of evidence value of glass fragments by likelihood ratio and Bayesian Network approaches, Anal. Chim. Acta 642 (1-2) (2009) 279–290, https://doi.org/10.1016/j.aca.2008.10.005.
[16] P.D. Maskell, G. Jackson, Application of a Bayesian network to aid the interpretation of blood alcohol (ethanol) concentrations in air crashes, Forensic Sci. Int. 308 (2020) 110174, https://doi.org/10.1016/j.forsciint.2020.110174.
[17] A.P. Dawid, I.W. Evett, Using a graphical method to assist the evaluation of complicated patterns of evidence, J. Forensic Sci. 42 (2) (1997) 226–231, https://doi.org/10.1520/JFS14102J.
[18] E. Charniak, Bayesian networks without tears, AI Mag. 12 (4) (1991) 50–63, https://doi.org/10.1609/aimag.v12i4.918.
[19] F. Taroni, A. Biedermann, S. Bozza, P. Garbolino, C. Aitken, Bayesian networks for probabilistic inference and decision analysis in forensic science, John Wiley & Sons, 2014.
[20] D. Taylor, A. Biedermann, T. Hicks, C. Champod, A template for constructing Bayesian networks in forensic biology cases when considering activity level propositions, Forensic Sci, Int.-Gen. 33 (2018) 136–146, https://doi.org/10.1016/j.fsigen.2017.12.006.
[21] A. Biedermann, S. Bozza, F. Taroni, Probabilistic evidential assessment of gunshot residue particle evidence (Part I): Likelihood ratio calculation and case pre-assessment using Bayesian networks, Forensic Sci. Int. 191 (1-3) (2009) 24–35, https://doi.org/10.1016/j.forsciint.2009.06.004.
[22] G. Jackson, C. Aitken, P. Roberts, Case assessment and interpretation of expert evidence, Guidance for judges, lawyers, forensic scientists and expert witnesses, Practitioner guide 4 (2015) 145p.
[23] S.C.A. Uitdehaag, A. Dragutinovic, A.J. Leegwater, T.H. Donders, I. Kuiper, F. Wagner-Cremer, Objective comparison of pollen assemblages from forensic soil traces, in: Forensic soil comparison: towards objective methods for a more robust evidential value, Utrecht University, Utrecht, 2021, pp. 55-72. https://doi.org/10.33540/652.
[24] D. Taylor, B. Kokshoorn, T. Hicks, Structuring cases into propositions, assumptions, and undisputed case information, Forensic Sci, Int.-Gen. 44 (2020) 102199, https://doi.org/10.1016/j.fsigen.2019.102199.
[25] I.W. Evett, G. Jackson, J.A. Lambert, More on the hierarchy of propositions: exploring the distinction between explanations and propositions, Sci. Justice 40 (1) (2000) 3–10.
[26] F. Taroni, S. Bozza, T. Hicks, P. Garbolino, More on the question 'When does absence of evidence constitute evidence of absence?' How Bayesian confirmation theory can logically support the answer, Forensic Sci. Int. 301 (2019) e59–e63, https://doi.org/10.1016/j.forsciint.2019.05.044.
[27] N. Fenton, D. Berger, D. Lagnado, M. Neil, A. Hsu, When 'neutral' evidence still has probative value (with implications from the Barry George Case), Sci. Justice 54 (4) (2014) 274–287, https://doi.org/10.1016/j.scijus.2013.07.002.
[28] A. Biedermann, T. Hicks, F. Taroni, C. Champod, C. Aitken, On the use of the likelihood ratio for forensic evaluation: Response to Fenton et al. Sci. Justice 54 (4) (2014) 316–318, https://doi.org/10.1016/j.scijus.2014.04.001.
[29] P. Juchli, A. Biedermann, F. Taroni, Graphical probabilistic analysis of the combination of items of evidence, Law Probab. Risk 11 (1) (2012) 51–84, https://doi.org/10.1093/lpr/mgr023.
[30] A. Martyna, G. Zadora, D. Ramos, Forensic comparison of pyrograms using score-based likelihood ratios, J. Anal. Appl. Pyrol. 133 (2018) 198–215, https://doi.org/10.1016/j.jaap.2018.03.024.
[31] G.S. Morrison, E. Enzinger, Score based procedures for the calculation of forensic likelihood ratios–Scores should take account of both similarity and typicality, Sci. Justice 58 (1) (2018) 47–58, https://doi.org/10.1016/j.scijus.2017.06.005.