A study of patterns produced when selected Tasmanian soil types are transferred to clothing: Application of digital photography with image processing to support visible observations

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Abstract

There is currently a void in published scientific knowledge in the interpretation of trace soil patterns on the surface of clothing fabric. In the same way that biological fluids, paint, glass and textile fibres are important trace evidence materials, soil is also likely to come into contact with offenders and victims because it is such a widespread and common material. A question often asked in trace evidence comparison is whether material, such as DNA, was transferred during the crime incident or deposited at some other time. Soil provides a likely surface for contact with a body that is being dragged. A method to visually interpret trace soil patterns on the surface of clothing fabric worn by victims or suspects is of particular importance to police and forensic scientists trying to gather forensic evidence to solve major crime. Visual analysis of this type of soil evidence may indicate what occurred during the perpetration of a crime.

Using a series of laboratory experiments and a simulated clothed human body, nearly 1000 experiments tested the soil transfer methods of either placing or dragging weighted fabric on a wet or dry soil surface. Sets of trace soil patterns were recorded; with many patterns unique to a specific method of soil transference. Twenty different anthropogenic and natural soil types and five fabric types [cotton, nylon, nylon-elastane, polyester-cotton and polar fleece (polyester brushed both sides)] were used to ascertain whether some trace soil patterns could universally occur across all soils and fabrics tested. Soil mineralogy and moisture content, irregularities on the fabric surface (such as raised seams) and appendages (such as buttons and metal buckles) had a greater influence on resulting trace soil patterns than the five types of fabrics tested. This influence was also dependent on the method of soil transfer used. Image processing computer software provided a cheap, accessible, objective and standardised method of providing numerical data on trace soil transferred to fabric. This analysis included Munsell soil colour analysis, the quantity and directionality of individual and aggregate trace soil objects transferred. Digital photographs were taken using a camera in natural and artificial lighting conditions of trace soil patterns on fabric. It was important that this occurred before the simulated clothed body was moved or clothing fabric removed; to keep trace soil patterns in original pristine condition.

The equipment used in this forensic soil analysis was kept as simple and portable as possible. This would make this method viable for a police crime scene photographer or forensic investigator working in the field, with limited access to expensive forensic equipment.

Using a white scale bar as a colour standard allowed image processing software to identify the Munsell soil colour of trace soil evidence from photographs taken under varying lighting conditions. In these initial experiments, image software was only programmed to recognise 25 out of the full range of 450 Munsell soil colours. Despite this limited programming, a unique range of dominant and subdominant Munsell soil colour peaks was produced from each photograph. When graphed, this numerical data provided a means to compare the soil origin of trace soil patterns on multiple items of clothing by their Munsell colour range. White coloured and homogenously woven fabrics were used to

minimise the programming required for image processing software to recognise trace soil objects. Due to this limited programming, soil objects < 100 μm or < 2 pixels were omitted from analysis.

If image software was developed specifically for forensic soil analysis of trace soil on clothing fabric, it could enable police with little or no forensic soil training to compare Munsell soil colours of trace soil evidence on clothing. This method would be relevant when comparing whether clothing items from victims and suspects showed a similar range of Munsell soil colours, these could then be given urgent attention in subsequent forensic testing procedures, such as XRD analysis. Once future software colourimetric development occurs, image processing has the potential to link the colour of trace soil objects on fabric with the source soil's mineralogy; without requiring the technical expertise to operate an expensive spectrophotometer.

This approach designed and developed a new method of forensic soil analysis in which trace soil patterns on clothing evidence is photographed, preferably at the crime scene, before the body is moved or clothing removed. Digital photographs can then undergo image processing analysis to confirm the method of soil transfer. This provides police and forensic investigators with a portable, financially accessible, objective and standardised method to use trace soil evidence on clothing to better understand the circumstances during the perpetration of a crime.

This methodology requires only a basic digital camera and image processing computer software to confirm trace soil patterns that can also be recognised by naked eye alone. Image software enables police and forensic investigators with little-to-no knowledge of forensic soil science to get numerical data on the Munsell soil colour range, the quantity of individual and aggregate soil objects transferred to clothing fabric and the directionality of trace soil transferred. Munsell soil colour analysis provides a method to compare the origins of trace soil on clothing by colour, without requiring an expensive spectrophotometer or access to an XRD machine and technicians to operate it. The quantity of soil objects transferred will help police to recognise whether soil was transferred when wet or dry. This will help to pinpoint the approximate time the body made contact with a soil surface. If a strong directionality exists within soil objects transferred, this indicates a body was dragged across a soil surface, rather than merely placed upon it.

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Structure of this thesis

The University of Adelaide encourages the publication of papers during candidature and permits theses to be presented as either a collection of published papers or a combination of papers and conventional chapters. The main body of this thesis comprises four papers either published, accepted or submitted to international peer- reviewed journals. Additionally, the Appendix consists of one refereed and published technical report corresponding with the published journal paper in chapter 2, supplementary data corresponding to the refereed and submitted paper in chapter 3.

Chapter 1 provides a brief review and overview of the need for new methods and approaches to make better use of forensic soil evidence in the form of trace soil patterns on clothing, and what part of the forensic soil information delivery this thesis addresses. The objectives and aims of this research are presented.

Chapter 2 provides for the first time, a method to identify trace soil patterns on clothing (bras) when a simulated clothed body is dragged across a soil surface. Conducted under laboratory conditions, a set of common and less frequently occurring soil transfer patterns are described and discussed.

A new method combining digital photographs of trace soil evidence on clothing with image processing computer software is utilised to provide objective, standardised numerical data on dominant and subdominant Munsell soil colours, the directionality and quantity of individual and aggregate soil objects transferred. The method is kept as simple, portable and accessible as possible to allow police and forensic investigators who are not soil experts to utilise this new method of forensic soil science to help police solve crime.

Chapter 3 describes the results of soil transfer experiments undertaken in the field, to ascertain whether trace soil patterns on clothing (bras) documented in the laboratory, can also be identified at a simulated crime scene. The methods of soil transference include either placing or dragging a clothed human rescue dummy across an Anthroposol and natural soil location.

Chapter 4 applies the laboratory method of dragging weighted clothing across a soil surface described in chapter 2 to discover whether trace soil patterns identified on nylon-elastane bras are universal across other clothing fabric types (cotton, polyester-cotton, nylon and polar fleece (polyester brushed both sides). Twenty different soil types are used. The influence of fabric type on the resulting trace soil pattern is discussed.

Chapter 5 follows the same methodology, soil and fabric types as chapter 4, but two different methods of placing weighted fabric on a soil surface are tested.

Chapter 6 provides a summary of objectives and findings for all four published papers with key conclusions. A focus is placed upon the Munsell soil colour findings from the previous chapters; describing the method of comparing trace soil evidence on various clothing items by the range of dominant and subdominant Munsell soil colour range and directionality of soil objects identified using image processing software. Limitations of conclusions are discussed; along with suggestions for future research priorities.

PUBLICATIONS RELATED TO THIS THESIS

The University of Adelaide encourages the publication of papers during candidature and permits theses to be presented as either a collection of published papers or a combination of papers and conventional chapters. The main body of this thesis, Chapters 2 to 5, comprises four journal papers. The references to those journal papers are provided below.

CHAPTER 2

Murray, Kathleen R, Fitzpatrick Robert W, Bottrill Ralph S, Berry Ron, Kobus Hilton. (2016) Soil transference patterns on bras: Image processing and laboratory dragging experiments. *Forensic Science International, 258*, 88-100. http://dx.doi.org/10.1016/j.forsciint.2015.10.009

CHAPTER 3

Murray, Kathleen R, Fitzpatrick Robert W, Bottrill Ralph S, Kobus Hilton. (2017) A study of the patterns produced when soil is transferred to bras by placing and dragging action: the application of digital photography and image processing to support visible observations. *Forensic Science International, 276*, 24-40. http://dx.doi.org/10.1016/j.forsciint.2017.03.026

CHAPTER 4

Murray, Kathleen R, Fitzpatrick Robert W, Bottrill Ralph S, Kobus Hilton. (2017) Soil transference patterns on clothing fabrics and plastic buttons: Image processing and laboratory dragging experiments. *Forensic Science and Criminology, 2*(1) 1-12. http://dx.doi.org/10.15761/FSC.1000109

CHAPTER 5

Murray, Kathleen R, Fitzpatrick Robert W, Bottrill Ralph S, Kobus Hilton. (2017). An investigation of the pattern formed by soil transfer when clothing fabrics are placed on soil using visual examination and image processing analysis. *Forensic Science and Criminology, 2*(1) 1-11. http://dx.doi.org/10.15761/FSC.1000110

Additional directly related major reports and supplementary data refereed and published, but not included in this thesis (as senior author)

Murray KR, Fitzpatrick RW, Bottrill R, Berry R, Woolley R, Doyle R, Kobus H (2015). Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: Laboratory dragging experiments. Acid Sulfate Soils Report no ASSC_096, University of Adelaide, 100 pages. http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=34394;m=view

Murray KR, Fitzpatrick RW, Bottrill RS, Kobus H (2016). Supplementary Information: A study of the patterns produced when soil is transferred to bras by placing and dragging action: the application of digital photography and image processing to support visible observations. This Supplementary information corresponds to the paper in chapter 3 and published online through Forensic Science International as a link embedded in this paper. doi:http://dx.doi.org/10.1016/j.forsciint.2017.03.026

Murray KR, Fitzpatrick RW, Kobus H, Berry R, Bottrill RS (2017). Using soil color analysis for forensic application at a crime scene. Color & Science. Retrieved from Munsell Color website. http://munsell.com/color-blog/color- analysis-forensic-application-crime-scene/

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1. CHAPTER 1 Thesis Scope and Outline

In the forensic science process of analyzing soil evidence on clothing, forensic soil scientists have tended to focus more on how soil's highly individual morphology and mineralogy can help police discover the location of crime scenes and grave sites; and to prove or disprove a suspect's alibi (e.g. Bergslien, 2012; Fitzpatrick, 2013a, 2013b; Fitzpatrick et al., 2009, 2011, 2012, 2014, 2017; Fitzpatrick & Raven 2012a,b; Murray, 1982, 2004; 2011; Murray and Tedrow, 1992; Pye, 2007; Ruffell & McKinley, 2005, 2008). Forensic methods have traditionally aimed to remove as much trace soil as possible from items of evidence; to analyze soil mineralogy and composition. Until recently, negligible interest has been given when analyzing trace soil evidence on objects; to recording or visually analyzing the soil marks themselves before soil is removed for analyses such as X-Ray Diffraction (XRD).

The work in this thesis was undertaken to address the current void in published scientific knowledge that interprets surface soil patterns on and or in clothing fabric. This is of particular importance to police and forensic scientists gathering forensic evidence to solve major crime. An attempt has been made in this thesis to focus on visually interpreting both the dominant and trace soil patterns on the surface of clothing fabric worn by victims or suspects; to provide evidence of what occurred during the perpetration of a crime.

During the Rayney murder trial in Western Australia in 2012, a gap in forensic soil knowledge was an important issue in the interpretation of soil evidence (Martin, 2012a, 2012b). A deceased female was found buried in park land. There was no evidence of violence at the burial site and it was deduced that the initial attack had occurred at a second location. Traces of brick dust and soil on the victim compared closely with a brick driveway and soil from the victim's front yard (Fitzpatrick et al. 2010, 2011) indicating that this was the location of the attack. A trace amount of red brick dust, combined with natural soil objects, were lodged against the buckles and fasteners of the victim's bra. This evidence relating to soil origin was accepted by the Judge that the initial attack on the victim occurred in the front yard of her home (Martin 2012a,b). However, during the trial the Judge stated that there was no evidence presented to explain how the brick dust from a red brick pavers from the victim's front paving may have transferred to the fabric and weave of the victim's bra (Martin, 2012b). An important question that arose in the trial was whether the soil from the victim's residence had been deposited by the action of dragging the body across the surface. The trial was before a judge and he concluded that there was no clear evidence to support the dragging proposition and that casual transfer of the soil could not be excluded (Martin 2012a,b).

The judge could not be convinced, beyond reasonable doubt, as to the circumstances by which trace soil patterns had resulted on the victim's clothing and boots. At that time, there was no established forensic soil method recognised by a court of law to visually interpret the likely method by which soil evidence had been transferred onto the surface of clothing fabric. The Judge suggested that soil evidence on her clothes may have been the result of normal daily activities. The Defendant was acquitted and Corryn Rayney's murder remains unsolved.

The circumstances in this case highlighted the lack of published research that would allow interpretation of trace soil patterns on clothed victims. Soil transference methods were limited to testing either the 'dragging' or 'placing' of a semi-clad female body on different natural and human made (Anthroposols) soil surfaces because these were the two transfer methods most hotly debated by forensic soil scientists on opposing sides during the Rayney murder trial. The lack of published literature testing even these most simple of soil transfer methods provided the incentive to field-test these two methods first. Resulting soil transfer patterns contained herein cannot be used to definitively prove a combination of these soil transfer methods or other situations not yet tested.

The initial question explored in this thesis was whether different soil types transferred to clothing using different transfer methods, left consistent and reproducible patterns that could be used to identify specific transfer methods. Research to be undertaken in highly controlled laboratory conditions will be conducted to: (i) test the transfer method of 'dragging' a simulated human body across soil surfaces to hopefully provide evidence that trace soil patterns are reproducible and a set of consistently occurring trace soil patterns could be identified, (ii) determine the directionality of soil transference patterns, (iii) quantify soil patterns using image processing computer software to record numerical data on all soil objects transferred ≥100μm to clothing and (iv) test a variety of likely soil transfer methods on different soil types, using five common clothing fabrics. This thesis will endeavour to provide a foundation for developing a new stream of forensic soil analyses transference methods capable of being accepted in a court of law.

There has been little recent research focusing on the transfer of soil particles onto textile fabrics since Locard (1930). What follows below is a review of the transfer of mostly human-made particles such as powder, glitter, glass fragments, acrylic and wool fibres (McDermott, 2013; Palmer, 2014; Roux & Robertson, 2013).

Bull *et al*. (2006b) built on the experiments of Pounds and Smalldon (1975a,b,c) who had originally explored the transfer and persistence of textile fibres. Bull *et al*. (2006b) documented the transfer and persistence of pollen, powder and metal particulates (lighter flint) on different types of materials; namely acrylic, cotton, denim, nylon, polyester and wool textiles (Bull, Parker, & Morgan, 2006). A swatch of the textile to be tested was attached to a coat, which was worn indoors and out for seven days. In one experiment, pollen was brushed onto the textile swatch. In a second experiment, fluorescent powder was mixed with wheat flour and evenly distributed to the textile swatch. In a third experiment, lighter flint particles were flicked onto the swatch by striking the flint of a 'Clipper' lighter, Bull *et al*. (2006b) concluded that the fabric weave of the material played a larger part in the transfer and persistence of particulates than did the type particulate. The transference method had an initial effect in the quantity of particles transferred, but the persistence of these particles over time tended to level out. "No discernible difference was identified with any variant of material type, moisture level or grain size with regard to persistence, spreading capability, tenacity, transfer or detection during experimentation" (Bull, Parker, et al., 2006). These previous particle transfer experiments provided key aims of the research to be undertaken in this thesis; namely whether soil type, moisture level and grain size influenced trace soil patterns on common clothing fabrics.

Hicks *et al.* (1996) explored the transfer and persistence of glass fragments on clothing, studying fragments transferred to the clothing of both the breaker standing 50cm away from the window glass and an accomplice standing 80cm away. Using either a hammer a stone or a pendulum, they discovered that up to seven fragments of glass could persist in clothing up to eight hours later. The number of fragments transferred depended upon the number of strikes, the distance between the windowpane and the person standing nearby, the time elapsed before forensic examination of the clothing and the weave of the garment (Hicks, Vanina, & Margot, 1996). In this thesis, based on the issues raised in Hicks *et al*. (1996), the persistence and relative fragility of trace soil evidence on clothing and the development of a forensic method will be developed and tested to provide a more pristine photographic record of trace soil evidence.

Unknown glitter particles persisting on clothing were compared to four known glitter types using light microscopy (Aardahl, Kirkowski, & Blackledge, 2005). They were characterised by end use, colour and shape to ascertain their relative uniqueness (Aardahl, 2003). The majority of clothing tested had cosmetic glitter particles persisting, even if the wearer did not use any products containing glitter. The transference and persistence of these particles on human skin was reliant on the body's natural moisture. Adhesion was increased with the addition of petroleum jelly. Numerical data analysis was not attempted in this experiment, due to the large number of unknown variables. In this thesis, trace soil objects on clothing from different sources will be characterised by Munsell soil colour (Munsell Color Company, 2009) and directionality on the fabric surface.

In their ground-breaking experiments involving the transfer of fibres between acrylic and woollen knitted garments and a cotton lab coat, Pounds and Smalldon (1975a) concluded that three processes were involved in causing fibres to be transferred onto recipient garments (Pounds & Smalldon, 1975a).

They established that during the first contact pass of transference, the majority of fibres transferred were loose short surface fragments or loose fibres pulled free by the friction of the contact. But during subsequent passes (eight contact passes in total), direct fragmentation of short fibres due to the pressure of the contact became the main cause of fibres being transferred; but at a rate of 50% less fibres than the initial first contact. The persistence of fibres on a garment worn up to thirty-four hours after first contact was not due to the electrostatic nature of the recipient garment fibres, but the strength of bond the remaining transferred fibres had made with the recipient garment (Pounds & Smalldon, 1975a). They observed that after the first four hours of transference of fibre evidence to worn knitted garments, only 18% of the transferred fibres remained. After 34 hours, only 3% of transferred fibres remained, signifying the most strongly bonded fibres. On an old, smooth cotton lab coat, transferred evidence was mostly lost within 30 minutes of contact being made, indicating a rapid decay curve (Pounds & Smalldon, 1975c). Natural soil particles may transfer and persist differently on clothing than the human-made particles tested.

Fine clay and silt-size fractions have a strong capacity to transfer and persist (Fitzpatrick, 2011, 2013a, 2013b; Fitzpatrick, Raven, & Forrester, 2009). Morgan and Bull (2007) noted that fine silt and clay size fractions of soil (<50-100 µm) have the capacity to stick to the surface of fabric for weeks (Morgan & Bull, 2007).

Morgan *et al.* (2009) stated that 'in order for trace evidence to have a high evidential value, experimental studies, which mimic the forensic reality are of fundamental importance. Such primary level experimentation is crucial to establish a coherent body of theory concerning the generation, transfer and persistence of different forms of trace physical evidence' (Morgan et al., 2009).

1.1 Methods

In this thesis, a wide range of natural soils and human made soils (Anthroposols) from Tasmania will be tested in soil transference experiments and be undertaken in both the laboratory and in the field. Using similar methodology to Pounds and Smalldon (1975a,b,c), fibre transference and persistence experiments, analogous experiments were designed to identify, which factors influence the transfer, persistence and relative quantity of natural and human-made soil on clothing fabrics. Unlike Pounds and Smalldon, soil and not wool fibre transfer characteristics will be tested. These new experiments will also differ by focusing specifically on nylon-elastane bras; with the variable element being multiple soil types and not multiple fabric types. Similar to Pounds and Smalldon (1975a,b,c), dragging will be the primary method of transference; but these new experiments will be run under both wet and dry conditions.

In order to achieve reproducible and consistent results, the weighted fabric will not be pushed by hand across the soil tray. This aspect of Pounds and Smalldon's method could not replicate a similar amount of force for every pass. Aware of this limitation, they experimented using greater and lesser force to ascertain whether this affected the number of fibres transferred. To maximise reproducibility of of results in the proposed experiments, weighted fabric will be dragged in timed runs across a soil tray using a drag-line.

Trace evidence on fabric and all bulk soil samples will then be described in accordance with methods use used in the CAFSS stage 1 classification of soil morphology (Fitzpatrick & Raven, 2016). Binocular and petrographic microscopy will also be used to assist to differentiate each sample and indicate likely provenance.

Image processing will be programmed to analyse digital photographs taken *in situ* of trace soil transfer patterns on fabric. This will be aimed to provide objective, quantifiable numerical data to assist or confirm the interpretation of soil transfer patterns as seen by the naked eye. The Trimble eCognition

Developer software will also be utilized and programmed to analyse Munsell Soil colour to identify and match trace soil on fabric to other trace soil evidence from the same location.

The works of Pounds and Smalldon did not require an analysis of the colour of the wool fibres for their transference and persistence experiments (Pounds & Smalldon, 1975a, 1975b, 1975c). They also did not have today's computer technology that enables a higher level of quantitative and objective results. But without their initial ground-breaking experiments, the design of the proposed soil transference experimental methods may never have come to pass. In addition, transfer testing will be conducted by simply 'placing' (i.e. not dragging) nylon-elastane bras. In addition, transfer testing will be conducted by simply "placing" (i.e. not dragging) nylon-elastane bras on various soil types. By testing different transfer methods, a comparison will be made as to whether transfer methods could be differentiated by different sets of transfer patterns produced.

1.2 Aim

The aim of this thesis was to improve upon the uses of forensic soil evidence to help police solve crime by understanding and more accurately interpreting how different soil transfer methods, namely dragging and two methods of placing a simulated clothed body on a wet or dry soil surface; may result in specific trace soil patterns on the surface of clothing fabrics. Trace soil patterns on clothing will be identified with the purpose of creating an objective, scientific and financially accessible method to interpret how trace soil is transferred to clothing on a clothed human body at a crime scene.

To explore the possible influences upon trace soil patterns on clothing fabric, twenty different wet and dry Anthroposols and natural soils from three distinct locations will be tested. The effect of five different fabric types on resulting trace soil patterns will also tested.

1.3 Trace soil evidence on clothing is important

Police and forensic investigators compare the chemistry, mineralogy and morphology of trace soil evidence transferred onto victims' and suspects' clothing during the perpetration of a crime, with known and questioned soil locations (e.g. Bergslien, 2012; Fitzpatrick, 2013a, 2013b; Fitzpatrick et al., 2009, 2011, 2012, 2014, 2017; Fitzpatrick & Raven 2012a,b; Murray, 1982, 2004; 2011; Murray and Tedrow, 1992; Pye, 2007; Ruffell & McKinley, 2005, 2008). This is particularly important when other forms of forensic evidence such as DNA, fingerprints or reliable witness testimony are absent. In order to understand the circumstances that occurred during or after an attack, as well as whether the victim was conscious and moving or unconscious or restrained and unmoving when their body made contact with a soil surface, it is critical to understand and document trace soil pattern evidence in order to accurately interpret these patterns. Visual evidence of trace soil patterns on clothing is currently not photographed 'in situ' before the body is moved or clothing removed.

1.4 How trace soil evidence is acquired

The current routine method for acquiring useable trace soil evidence is to scrape and remove as many soil particles from clothing fabric evidence as possible, to procure a sample large enough to undergo X-ray Diffraction (XRD), Nondispersive Infra-Red (NDIR), light and Scanning Electron Microscopic (SEM) analysis of soil chemistry and mineralogy. These analyses are combined with naked eye or colourimetric analysis of Munsell soil colour and other morphological soil characteristics (Fitzpatrick & Raven, 2016).

1.5 How trace soil evidence is used

Once all necessary soil analyses have been completed and trace soil evidence has been characterised at the high standard required in a court of law, bulk soil samples from known and questioned soil locations are compared. The alibis of known suspects can be proven or discredited according to the findings of forensic soil experts (Bull, Parker, et al., 2006; Fitzpatrick & Raven, 2010, 2012a, 2012b; Fitzpatrick, Raven, & Self, 2011, 2012; Morgan & Bull, 2007; Morgan et al., 2009; Murray, 1982, 2004; 2011; Murray and Tedrow, 1992; Pye, 2007; Ruffell & McKinley, 2005, 2008).

1.6 Problems with the use of trace soil evidence

Forensic soil science is an emerging area, where much research is still required to aid police investigations and expert testimony. Although great strides have been taken in analysis of forensic soil evidence, a notable lack of research interpreting the transfer of trace soil evidence on clothing indicates this aspect of forensic analysis is not being used to its full potential to help police solve crime (Di Maggio et al., 2017; Fitzpatrick, Raven & Self, 2017).

During forensic analyses of soil materials on clothing, especially when there are few soil materials present it is often necessary to remove as much soil material as possible from clothing for mineralogical and chemical analyses (Fitzpatrick & Raven, 2016). In the recent Louise Bell cold case murder investigation, forensic soil scientists were requested to interpret trace soil evidence remaining on a pyjama top; several decades after the bulk of this soil evidence had been vacuumed off. Fitzpatrick (2015) conducted a series of laboratory transference shaking experiments with a clean strip of pyjama top fabric and using scanning electron microscopy (SEM) observed that the mineral particles were dominantly located on the surface of pyjama fabric. However, in the heavily stained seams of the questioned pyjama top the mineral particles were observed by SEM to be mostly deeply impregnated in gaps between the fibres of the fabric, which likely originated under water with some force being applied on the pyjama top (Fitzpatrick & Raven, 2016; Di Maggio et al., 2017). The unintentional effect of traditional forensic testing, such as the cutting up of victim's clothing during the investigation of the Western Australian Rayney murder case (Martin, 2012a, 2012b), was the near-complete removal of trace soil patterns that may have enabled a better understanding of the circumstances befalling the murder victim. Hence, removing soil from clothing for external analysis destroys pristine trace soil patterns that could provide a record of the method of soil transfer and therefore the circumstances during and/or after an attack. Trace soil patterns have the potential to indicate whether the victim was alive and struggling or incapacitated when their body made contact with a soil surface.

1.7 Decision maker requirements

During some Australian criminal investigations, the findings of forensic soil experts have proven as integral to the outcome of court proceedings (Fitzpatrick, 2011; Fitzpatrick, Raven, & Self, 2014). Although research has been undertaken to understand the properties of other trace particulates on clothing (e.g. Bull, Morgan, Sagovsky, & Hughes, 2006; French, Morgan, Baxendell, & Bull, 2012; Lepot, Vanden Driessche, Lunstroot, Gason, & De Wael, 2015; Scott, Morgan, Jones, & Cameron, 2014; Stoney & Stoney, 2015), the demand now is for a new scientific and objective method that would enable forensic soil evidence to better aid the interpretation of the circumstances of an attack on a victim.. In the Western Australian Rayney homicide case, forensic soil experts were not permitted by the judge to use trace soil patterns on the victim's clothing to decipher the method of soil transfer during the initial attack (Martin, 2012a, 2012b).

1.8 Delivery of trace soil evidence, the issue that this thesis addresses

The prime objectives of the work in this thesis will be to develop improved methods:

1. Identify and interpret soil patterns on clothing fabric that would assist in determining the mode of transfer.
2. Conduct tests using only a digital camera and computer with relevant software to make the examination of soil transfer patterns simple to introduce in police case work. Although police in most developed nations have access to soil science experts with expensive soil analysis equipment required to run analyses, limitations in funding or a massive case backlog of evidence can lead to delays in processing this soil evidence. As a consequence, user-friendly methods would enable police to do preliminary non-destructive testing of trace soil evidence 'in house'.
3. Conduct image processing analyses of Munsell soil colour of trace soil patterns on the victims' and suspects' clothing to enable important soil evidence to undergo further analysis. This approach will also allow police to determine whether the victim was struggling or incapacitated when their body made contact with a soil surface and also indicate the method by which it did so.
4. Conduct laboratory and field soil transfer experiments to create reproducible trace soil patterns using the transfer methods of placing or dragging weighted fabric (simulating a clothed human body) across a soil surface.

5. Conduct tests using the naked eye to record the initial soil patterns followed by digital photography and photomicrography to better quantify soil patterns on clothing (i.e. apply image processing software to identify soil objects ≥100μm on clothing fabric to better quantify and or confirm the initial visual analyses of trace soil patterns).
6. Conduct tests on a wide range of soil types from different locations in Tasmania (Figure 1-1) to determine the influence of Anthroposols (human-made soils) and natural soil types and moisture content (wet or dry soil) on resulting soil transfer patterns.
7. Conduct tests on the effect of five fabric types.

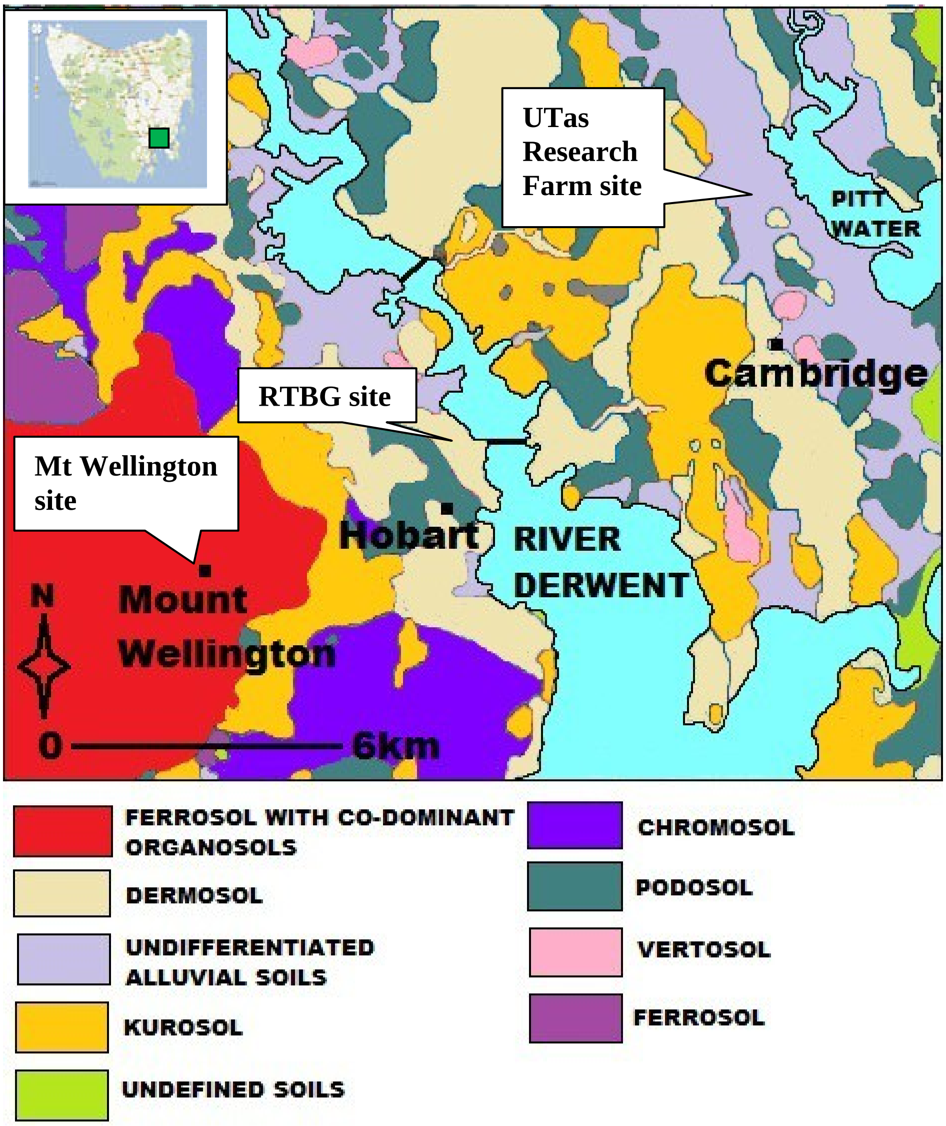

Figure 1-1 Soil map encompassing the three soil site areas of Mount Wellington, Hobart and Cambridge, Tasmania (modified from: Australian Soil Resources Information System, 2013)

1.9 Delivery of forensic soil evidence, proposed approach developed in this thesis

The full potential of trace soil evidence on clothing has not been fully utilised because of a lack of scientific research into identifying soil transfer patterns and understanding the circumstances by which these patterns are produced on clothing fabric.

Many police forensic experts are not soil scientists and their lack of training and confidence in correctly handling this easily contaminated or disfigured evidence can lead crime scene investigators to either discard or accidentally destroy this evidence through robust testing procedures.

In developing nations, lack of funding or access to expensive and technically prohibitive forensic equipment such as spectrophotometers and SEM can cause soil evidence to be disregarded.

To deliver this vital forensic soil information, the following issues should be addressed:

a) Develop and produce on a commercial scale affordable and fully automated image processing computer software, with an online help manual translated in all major languages. The help manual would teach the operator how to use image processing software to analyse digital photographs of trace soil patterns on clothing fabric. Image software would be programmed to produce numerical data on trace soil patterns, to produce understandable graphs detailing the Munsell soil colour range and quantity of trace soil objects transferred (Munsell Color Company, 2009). Rose diagrams would be incorporated into the software to illustrate whether soil objects show any directionality in their placement on fabric (Holcombe, 2011). This would also help to indicate the method of transfer and whether the victim was struggling or incapacitated when their body made contact with a soil surface.

b) Provide an online and/or printed guide to the naked eye techniques used in this thesis to identify trace soil patterns on clothing fabric and interpret their method of transfer; as well as photographic tips to best record pristine trace soil patterns on clothed bodies at a crime scene.

c) Produce a grey scale bar to provide the necessary scale when taking digital photographs of soil evidence on clothing and to act as a colour standard. This would not only allow police to compare the sizes of trace soil objects, but also enable image processing software to correctly analyse the dominant and subdominant Munsell soil colour range of trace soil on clothing; regardless of the natural or artificial lighting conditions at the crime scene or the digital camera used.

The aim of this thesis was to improve upon the uses of forensic soil evidence to help police solve crime by understanding and more accurately interpreting how different soil transfer methods, namely dragging and two methods of placing a simulated clothed body on a wet or dry soil surface; result in specific trace soil patterns on the surface of clothing fabrics. Trace soil patterns on clothing were identified with the purpose of creating an objective, scientific and financially accessible method to interpret how trace soil is transferred to clothing on a clothed human body at a crime scene.

To explore the possible influences upon trace soil patterns on clothing fabric, twenty different wet and dry Anthroposols and natural soils from three distinct locations in Tasmania will be tested. The effect of five different fabric types on resulting trace soil patterns will also be tested. The following table provides a summary of the structure and objectives, soil-landscapes and end user information of each chapter in this thesis:

Chapter	**Delivery objective**	**Landscape** *Climate* **Soil type**	**Information is used for**
2	Identify trace soil patterns on clothing when dragged across a soil surface.	Flat urban *Temperate* **Anthroposols and natural soils**	Enabling police forensic investigators to identify when a body has been dragged across a soil surface during an attack.
3	Identify trace soil patterns of dragging and placing in the field.	Flat urban *Temperate* **Anthroposols and natural soils**	Helping police recognise trace soil on clothed bodies at a crime scene.
4	Study the influence fabric types on trace soil patterns produced by dragging.	Mountainous, sloping-to-flat rural and flat urban *Temperate* **Anthroposols and natural soils**	Police to recognise trace soil patterns of from different clothing fabric types dragged across different soil types.
5	Study the influence fabric types on trace soil patterns produced by placing.	Mountainous, sloping-to-flat rural and flat urban *Temperate* **Anthroposols and natural**	Police to recognise trace soil patterns of different clothing fabric types placed upon different soil types.
6	Summary review of findings of papers, image processing of Munsell colour analysis and trace soil directionality.	Mountainous, sloping-to-flat rural and flat urban *Temperate* **Anthroposols and natural soils**	Summarising and describing findings

1.9 References

Aardahl, K. (2003). Evidential value of glitter particle trace evidence. National University.

Aardahl, K., Kirkowski, S., & Blackledge, R. (2005). A target glitter study. *Sci Justice, 45*, 7-12.

Australian Soil Resources Information System (2013), Australian Soil Resources Information System (ASRIS), Maps and Database. CSIRO Land and Water, Canberra, ACT, Australia.

Bull, P., Morgan, R., Sagovsky, A., & Hughes, G. (2006). The transfer and persistence of trace particulates: experimental studies using clothing fabrics. *Sci. Just., 46*(3), 185-195. doi:http://dx.doi.org/10.1016/S1355-0306(06)71592-1

Bergslien, E. (2012). *An Introduction to Forensic Geoscience*. USA: Wiley-Blackwell.

Bull, P., Parker, A., & Morgan, R. (2006b). The forensic analysis of soils and sediment taken from the cast of a footprint. *Forensic Sci Int., 162*, 6-12.

Di Maggio, R., Al Naimi, K., Barone, P., Salvador, F., Dawson, L., Dixon, R., . . . Villalba, D. (2017). Global developments in forensic geology. *Episodes*, *40*(2), 120-13. http://dx.doi.org/10.18814/epiiugs/2017/v40i2/017014

Fitzpatrick, R. (2011). The value of soil in criminal investigations. Soil Forensics profile Newsletter. The Australian Society for Soil Science Inc, Victoria pp. 5-6.

Fitzpatrick, R. (2013a). Soil: Forensic Analysis. In A. Jamieson & A. Moenssens (Eds.), Wiley Encyclopedia of Forensic Science. Chichester: John Wiley. http://dx.doi.org/10.1002/9780470061589.fsa096.pub2 Published 18th September 2013). http://onlinelibrary.wiley.com/book/10.1002/9780470061589

Fitzpatrick, R. (2013b). Soils. In J. Siegel & P. Saukko (Eds.), Encyclopedia of Forensic Sciences, Second Edition, (pp. 206–212). Waltham, USA: Academic Press. http://dx.doi.org/10.1016/B978-0-12-382165- 2.00113-6 (ISBN: 978-0-12-382166-9)

Fitzpatrick, R. (2015). *Analyses of four questioned soil samples on a pyjama top and fourteen control samples from the Onkaparinga river region relating to the Louis Bell investigation by SAPOL.* Retrieved from Adelaide, South Australia:

Fitzpatrick, R., & Raven, M. (2012a). The State of Western Australia v. Lloyd Patrick Rayney Trial: Request for supplementary statement relating to extraction of particulate material from bra. Centre for Australian Forensic Soil Science, pp. 1-17.

Fitzpatrick, R., & Raven, M. (2012b). How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists. *Soil Horizons*. 53 (5), 14-29. doi:http://dx.doi.org/10.2136/sh12-05-0016

Fitzpatrick, R., & Raven, M. (2016). Guidelines for Conducting Criminal and Environmental Soil Forensic Investigations (Version 10.1). Report CAFSS_076, Centre for Australian Forensic Soil Science, 46pp. http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=35757;m=view (accessed 26 December, 2016).

Fitzpatrick, R., Raven, M., & Forrester, S. (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). Netherlands: Springer Science+Business Media B.V. doi:http://dx.doi.org/10.1007/978-1-4020-9204-6_8

Fitzpatrick R., Raven, M., & Self, P. (2011). Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to Operation Dargan. Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_080. 27 May 2011. 116pp.

Fitzpatrick, R., Raven, M., & Self, P. (2012). Soil as significant evidence in a sexual assault case. In L. Burkitt & L. Sparrow (Eds.), *Proceedings of the 5th Joint Australian and New Zealand Soil Science Conference: Soil solutions for diverse landscapes*. Hobart: Australian Society of Soil Science Inc.

Fitzpatrick, R., Raven, M., & Self, P. (2014,). *Clay mineralogy as significant evidence in 4 murder investigations involving a wide range of earth materials from Perth, Adelaide, Melbourne and Sydney.* Paper presented at the Proceedings 23rd Australian Clay Minerals Society Conference, Perth.

Fitzpatrick, R., Raven, M., & Self, P. (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. http://dx.doi.org/10.18814/epiiugs/2017/v40i2/017017

French, J., Morgan, R., Baxendell, P., & Bull, P. (2012). Multiple transfers of particulates and their dissemination within contact networks. *Science and Justice, 52*(1), 33-41. doi:http://dx.doi.org/10.1016/j.scijus.2011.05.001

Hicks, T., Vanina, R., Margot, P. (1996). Transfer and persistence of glass fragments on garments. *Sci. Justice, 36*, 101-107.

Holcombe, R. (2011). GEOrient. Queensland, Australia: School of Earth Sciences, University of Queensland.

Lepot, L., Vanden Driessche, T., Lunstroot, K., Gason, F., & De Wael, K. (2015). Fibre persistence on immersed garment - Influence of knitted recipient fabrics. *Science and Justice, 55*, 248-253. doi:http://dx.doi.org/10.1016/j.scijus.2015.02.006

Locard, E. (1930). Analyses of dust traces parts I, II and III. *American Journal of Police Science, 1*, 276-98, 401-18, 496-514.

Martin, B. (2012a). Judgement summary: The State of Western Australia v. Rayney. [No 3]. WASC, 404 (INS 83 of 2011): 1-13.

Martin, B. (2012b). The State of Western Australia v. Rayney. [No 3]. WASC, 404: 1-369.

McDermott, S. (2013). Trace evidence: Transfer, persistence and value. In J Siegel (Ed.), Encyclopedia of forensic sciences. Waltham: Academic press.

Morgan, R., & Bull, P. (2007). Forensic geosciences and crime detection: Identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale, 127*(2), 73-89.

Morgan, R., Cohen, J., McGookin, I., Murly-Gotto, J., O'Connor, R., Muress, S., Freudiger-Bonzon, J., Bull, P. (2009). The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Sci Justice, 49*, 277-285.

Morgan, R., Freudiger-Bonzon, J., Nichols, K., Jellis, T., Dunkerley, S., Zelazowski, P., & Bull, P. (2009). The forensic analysis of sediments recovered from footwear. In K. Ritz, L. Dawson, & D. Miller (Eds.), Criminal and Environmental Soil Forensics (pp. 253-269). Netherlands: Springer.

Munsell Color Company. (2009). *Munsell Soil Color, Book*. Michigan: Munsell Color X-rite.

Murray R.C. (1982). Forensic examination of soil. In Forensic science handbook. R. Saferstein, Ed. Englewood Cliffs, NJ., Prentice Hall. 1.

Murray R.C. (2004). Evidence from the Earth: Forensic Geology and Criminal Investigation. Mountain Press Publishing, Missoula, MT. pp 227.

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

Murray R.C. and Tedrow, J.C.F. (1992). Forensic Geology. Prentice Hall, New, Jersey, 1992.
Palmer, R. (2014). Fibers: Transfer, persistence and recovery. In Wiley Encyclopedia of Forensic Science. (pp. 1-10).
Pounds, C., & Smalldon, K. (1975a). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. III: A preliminary investigation of the mechanisms involved. *Journal Forensic Science Society, 15*, 197-207.
Pounds, C., & Smalldon, K. (1975b). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part I: fibre transference. *Journal Forensic Science Society, 15*, 17-27.
Pounds, C., & Smalldon, K. (1975c). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part II: fibre persistence. *Journal Forensic Science Society, 15*, 29-37.
Pye K. (2007). Geological and Soil Evidence: Forensic Applications. CRC, Boca Raton, FL.
Ruffell A. & McKinley J. (2005). Forensic Geoscience: applications of geology, geomorphology and geophysics to criminal investigations. Earth-Science Reviews. 69: 235–247.
Ruffell A. & McKinley J. (2008). Geoforensics. John Wiley & Sons, Ltd, Chichester.
Roux, C., & Robertson, J. (2013). Fibers. In J. Siegel (Ed.), Encyclopedia of Forensic Sciences. Waltham: Academic Press.
Scott, K., Morgan, R., Jones, V., & Cameron, N. (2014). The transferability of diatoms to clothing and the methods appropriate for their collection and analysis in forensic geoscience. *Forensic Sci International, 241*, 127- 137. doi:http://dx.doi.org/10.1016/j.forsciint.2014.05.011
Soil Survey Staff (2014). Keys to Soil Taxonomy. United States Department of Agriculture, Natural Resources Conservation Service, Washington D.C..
Soil Survey Staff (1999). Soil Taxonomy: A Basic System of Soil Classification for Making and Interpreting Soil Surveys. Second edition. USDA-Natural Resources Conservation Service, Agriculture Handbook Number 436.
Stoney, D., & Stoney, P. (2015). Critical review of forensic trace evidence analysis and the need for a new approach. *Forensic Sci International, 251*, 159-170. doi:http://dx.doi.org/10.1016/j.forsciint.2015.03.022

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Name of Principal Author (Candidate)	Kathleen Murray		
Contribution to the Paper	I wrote this paper. It was then edited by my Principal Supervisor, Rob Fitzpatrick.		
Overall percentage (%)	95%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

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Name of Co-Author	Rob Fitzpatrick		
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Development of soil forensic methods and databases from targeted locations in Tasmania to assist Police

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Across Australia, Police rely heavily on DNA evidence and witness testimony to solve crime. Historically, this provided enough evidence to charge an offender. But in recent major crime investigations, soil evidence compared and characterised using the approach and methods outlined by CAFSS (Fitzpatrick and Raven 2012), has proved crucial in successfully assisting police and convicting offenders in Australian Courts of Law. However, most Police forensic laboratories are ill-equipped to analyse forensic soil evidence. A rising tide of unsolved 'cold case' major crime, with no DNA evidence or reliable witnesses, is 'gathering dust' on Police books. With assistance from Tasmania Police, forensic soil data from specific soil types at the following targeted locations will be gathered, to assist with new avenues of inquiry:

- Key soil catenary sequences near Richmond, Hobart will be used to test distinctness of mixed pit spoil and single pit spoils via "credible scenarios of crime scene approach".
- Human-made or human-transported soils (Anthroposols) in a high-crime area of Hobart.
- Organic-rich 'peaty' soil (Organosols) from high-altitude in Tasmania.
- Coastal and inland Acid Sulfate Soils from Tamar Estuary, Launceston.
- Cultivated soil from commercial opium poppy plantations across Tasmania.
- Use of spectrophotometry to quantify colour of a diverse range of Tasmanian soil types.

Soil samples will be characterised according to the four-stage process developed by CAFSS, including detailed soil morphology characterisation of soil, mineral and organic composition using a combination of X-ray diffraction (XRD), magnetic susceptibility, heavy mineral and magnetic fractionation. Soil-regolith conceptual models and maps will complete analysis of each site. The capacity of different soil properties to discriminate between not only diverse soil types, but very similar soil samples from close geographic locations, as well as soil trace evidence, shall be investigated.

Reference

Fitzpatrick, R. W. and M. D. Raven. (2012). Guidelines for conducting criminal and environmental soil forensic investigations (Version 6). Report No. CAFSS_076. Australia: Centre for Australian Forensic Soil Science http:// www.clw.csiro.au/cafss/. (accessed 26 April. 2012).

2. CHAPTER 2 Soil transference patterns on bras: Image processing and laboratory dragging experiments

This chapter develops a methodology that will enable trace soil patterns on clothing fabric to be consistently reproduced under laboratory conditions. Using the transfer method of dragging, a simulated human body is dragged across a wet or dry soil surface. A set of trace soil patterns are identified and discussed with the aim to help police solve crime.

For the very first time, digital photographs of trace soil on clothing are combined with image processing computer software to provide numerical data on the Munsell soil colour range, quantity and directionality of individual and aggregate soil objects.

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Contribution to the Paper	I wrote the initial and subsequent drafts. These were edited by Rob Fitzpatrick and Hilton Kobus. XRD analysis included in this paper was undertaken by Ralph Bottrill. Ron Berry programmed the image processing eCognition Developer software and taught me how to use the program.		
Overall percentage (%)	90%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

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Name of Co-Author	Rob Fitzpatrick		
Contribution to the Paper	Rob edited each draft submitted.		
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Name of Co-Author	Hilton Kobus		
Contribution to the Paper	Hilton extensively edited each draft submitted.		
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Name of Co-Author	Ron Berry		
Contribution to the Paper	Ron Berry followed my specifications when programming image processing software to identify soil objects, their directionality and Munsell soil colour on white fabric of varying fabric types.		
Signature		Date	27/04/2017

Name of Co-Author	Ralph Bottrill		
Contribution to the Paper	Ralph provided technical expertise with XRD analyses and interpretation. Ralph also offered suggestions in final editing stages.		
Signature		Date	27/04/2017

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Soil transference patterns on bras: Image processing and laboratory dragging experiments

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ABSTRACT

In a recent Australian homicide, trace soil on the victim's clothing suggested she was initially attacked in her front yard and not the park where her body was buried. However the important issue that emerged during the trial was how soil was transferred to her clothing. This became the catalyst for designing a range of soil transference experiments (STEs) to study, recognise and classify soil patterns transferred onto fabric when a body is dragged across a soil surface.

Soil deposits of interest in this murder were on the victim's bra and this paper reports the results of anthropogenic soil transfer to bra-cups and straps caused by dragging. Transfer patterns were recorded by digital photography and photomicroscopy.

Eight soil transfer patterns on fabric, specific to dragging as the transfer method, appeared consistently throughout the STEs. The distinctive soil patterns were largely dependent on a wide range of soil features that were measured and identified for each soil tested using X-ray Diffraction and Non-Dispersive Infra-Red analysis.

Digital photographs of soil transfer patterns on fabric were analysed using image processing software to provide a soil object-oriented classification of all soil objects with a diameter of 2 pixels and above transferred. Although soil transfer patterns were easily identifiable by naked-eye alone, image processing software provided objective numerical data to support this traditional (but subjective) interpretation.

Image software soil colour analysis assigned a range of Munsell colours to identify and compare trace soil on fabric to other trace soil evidence from the same location; without requiring a spectrophotometer. Trace soil from the same location was identified by linking soils with similar dominant and sub-dominant Munsell colour peaks.

Image processing numerical data on the quantity of soil transferred to fabric, enabled a relationship to be discovered between soil type, clay mineralogy (smectite), particle size and soil moisture content that would not have been possible otherwise. Soil type (e.g. Anthropogenic, gravelly sandy loam soil or Natural, organic-rich soil), clay mineralogy (smectite) and soil moisture content were the greatest influencing factors in all the dragging soil transference tests (both naked eye and measured properties) to explain the eight categories of soil transference patterns recorded.

This study was intended to develop a method for dragging soil transference laboratory experiments and create a baseline of preliminary soil type/property knowledge. Results confirm the need to better understand soil behaviour and properties of clothing fabrics by further testing of a wider range of soil types and clay mineral properties.

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1. Introduction

In a recent homicide matter in Australia [1,2], the results of soil examinations were the only forensic science evidence obtained in the case. Despite burial for eight days in natural soil in neighbouring parkland, the mineralogy and descriptive characteristics of trace soil on the victim's clothing and shoes showed an extremely strong degree of comparability of originating from distinctly different anthropogenic soils from the victim's place of residence [1–4]. This forensic evidence indicated the victim could have been attacked at her home and then transported to the burial site. An important question that arose in the trial was whether the soil from the victim's residence had been deposited by the action of dragging the body across the surface. The trial was before a judge and he concluded that there was no clear evidence to support the dragging proposition and that casual transfer of the soil could not be excluded [1,2].

Current forensic soil examination has a range of sophisticated analytical techniques available to compare soil with possible places of origin and can provide compelling evidence for an association with a suspected source [5–13]. As documented by Sugita and Marumbo [14], variations in soil colour provide one of the most distinguishing characteristics of trace soil evidence.

However in the homicide matter referred to above, the important question was not about the complexities of soil science but the much more fundamental question of how the soil was deposited on the clothing. A search of the literature revealed an absence of any studies into this topic. Studies to date have mostly involved the transfer of manufactured materials [15] such as powder [16], glitter [17,18], glass fragments [19], acrylic and wool fibres [20–23]. There has been no recent research focusing on the transfer of soil particles onto textile fabrics since Locard [24]. This identified a need for systematic studies to be conducted to determine whether a range of soil types deposited by dragging produced characteristic features that would allow this mode of transfer to be inferred [25].

The dragging method of soil transfer to fabric alleged during the homicide matter inspired this paper's soil transference experiments. Relatively abundant soil deposits were on the victim's bra [1–4]. This item of clothing was therefore selected as the starting point for a series of soil transfer experiments (STEs) conducted on a range of natural and anthropogenic soils from Royal Tasmanian Botanical Gardens, Hobart, Tasmania, Australia [26].

One of the earliest studies into transfer and persistence was that of Pounds and Smalldon [20–22] who investigated the transfer of textile fibres. They achieved fibre transfer by pushing a weighted fabric across an underlying fabric. This methodology was adapted for our studies for a range of soil transference experiments (STEs) where weighted bra-straps and cups were used to simulate a victim dragged across soil. Image processing software was adapted to analyse digital photographs of the soil patterns produced in the STEs to provide an objective methodology for determining the characteristics caused by dragging.

Classifying soils for a particular purpose involves the ordering of soils into groups or types with similar properties and for potential end uses. In general, soil classification systems currently used in most countries involve the use of the following three broad approaches [27].

- General-purpose broad soil classifications such as World Reference Base [28] or Soil Taxonomy [31], which communicate soil information at international scales; and national scale classifications, such as Australian Soil Classification [29], shown in Table 1.
- State, provincial or regional soil classifications, which are designed both to assist with "user-friendly" communication of soil information and to account for the occurrence of soils that impact on existing and future industry development and prosperity [27].
- Special-purpose and more technical soil classification systems, which are used for local or single-purpose applications such as in Soil Forensics [27]. These special-purpose systems generally involve using plain language names for soil types (e.g. anthropogenic, gravelly sandy loam soil or natural, organic-rich soil) for users such as police [27] but must also correlate with the general-purpose international and national classifications.

The soil classifications used in this paper incorporate international and national general-purpose classifications as well as a local special-purpose soil classification system as shown in Table 1; to be of global relevance to the greatest number of forensic investigators and researchers.

2. Materials and methods

2.1. Soil samples

Forensic soil examination is complex because of the diversity and heterogeneity of both naturally occurring soils (e.g., crystalline minerals, organic matter) and anthropogenic soils that often contain very small, sometimes even trace amounts of manufactured materials such as brick fragments and road gravel. Such diversity and heterogeneity have enabled forensic soil examiners to distinguish between soils, which may appear to be similar [5–11].

Murray et al. [26] contains detailed soil morphological descriptions and classifications on the 5 anthropogenic soils (Technosols, Anthrosols or Human-altered and Human-transported (HAHT; [31] soils) and 2 natural soil samples, which are summarised in Tables 1 and 2. Five anthropogenic and two natural soil samples originated from the Royal Tasmanian Botanical Gardens (RTBG) in Queens Domain, Hobart, Tasmania, Australia (Fig. 1). The natural soil type in the RTBG classify as Dermosols (a light clay over heavy black clay) [29] or Cambisols [28]; but the majority of these grounds in the RTBG (green cross-hatched area) have been radically modified to create roads, walls, specialty gardens and smooth flat lawn surfaces [30] (Fig. 2). As a consequence, the dominant soils in the RTBG and on Hobart's waterfront as shown in Fig. 1 (shaded a purple colour) comprise the following anthropogenic soil types:

- Anthroposols in accordance with the Australian Soil Classification [29] or,
- Technosols and Anthrosols in accordance with the World Reference Base [28].
- Human-altered and Human-transported material (HAHT) as defined in Soil Taxonomy [31].

Five samples were classified as Anthroposols, with four containing high amounts (90%) of gravel (>2 mm); including one with brick fragments (Table 1). Anthroposols are characterised by a strong spatial heterogeneity (Fig. 2) and usually contain a large array of known historical information such as brick fragments, which has been proved very useful in understanding and quantifying soil differences in forensic soil comparisons [6–13]. Two natural soil samples were taken from distinct horizons of one soil profile on the SE boundary. The top horizon consisted of undecomposed leaf matter, taken from 5 to 0 cm above the soil surface; with a second horizon of underlying mineral soil.

Analysis of carbon contents (by NDIR) and mineralogy (by X-ray diffraction) was undertaken on all soils except a non-mineral based horizon consisting of undecomposed leaves, because it did not

Table 1
Soil type and morphology, Australian Soil Classification of soil materials [29] and the approximate corresponding World Reference Base for Soil resources class [28] provided by Murray et al. [26].

Locality (depth cm)	Centre for Aust. Forensic Soil Science (CAFSS) code	Munsell[a] Soil Colour <2 mm fraction (wet) (dry)	Soil type[b]	Brief description	The Australian soil classification	The world reference base for soil resources
Soil 1: Rose Garden Path (0–10 cm)	110.5.1	Dark brown 7.5YR 3/2 Brown 7.5YR 5/2	Anthropogenic, gravelly sandy loam soil	Gravel (90%; arkosic sandstone and andesitic-to-weathered mafic igneous rock) loamy sand, water repellent, 0.7% carbon (C).	Spolic Anthroposol, very gravelly, sandy, very shallow	[c]Spolic Technosol (Densic)
Soil 2: Rose Garden Path near wall (0–10)	110.6.1	Dark brown 7.5YR 3/2 Brown 7.5YR 5/2	Anthropogenic, gravelly sandy loam soil	Gravel (90%; as above), sand, non water repellent, 5% brick fragments, 1.2% C.	Spolic Anthroposol, very gravelly, sandy, very shallow	[c]Spolic Technosol (Densic, Transportic)
Soil 3: brick fragments (0–2)	110.6.2	Red 2.5YR 5/8 Light red 2.5YR 7/8	Anthropogenic, brick fragment-rich soil	Gravel (90%), sandy, water repellent, weathered brick fragments (0.5–4 cm), 1.2% C.	Urbic Anthroposol, very gravelly, sandy, very shallow	[c]Urbic Ekranic technosol (Transportic)
Soil 4: rose garden bed (0–10)	110.7.1	Black 10YR 2/1 Black 7.5YR 2.5/1	Anthropogenic, organic-rich sandy loam soil	Gravel (15% coarse river sand), loamy sand (25%), water repellent, 30% fine compost, 30% composted pine bark, 14% C.	Hortic Anthroposol, non-gravelly, sandy, shallow	[d]Hortic Anthrosol (Escalic)
Soil 5: Japanese garden bed (0–10)	110.8.1	Dark reddish grey 2.5YR 3/1 Reddish grey 2.5YR 6/1	Anthropogenic, quartz-rich gravelly sandy soil	Gravel (90%: ~80% rounded quartz, 10% sub-rounded to angular dolerite; 5% ironstone), loamy sand, water repellent, 3% C.	Spolic Anthroposol, very gravelly, sandy, very shallow	[c]Spolic technosol (Grossartefactic, Transportic)
Soil 6: South-east boundary (5– 0)	110.9.1	Leaves not analysed for Munsell soil colour by naked eye	Surface Natural, organic-rich soil	Undecomposed Leaves (60%) and decomposed (40%)	Humose, mesotrophic	[e]Eutric Cambisol (Humic)
Soil 7: South-east boundary (0–10)	110.9.2	Very dark brown 10YR 2/2 Very dark brown 7.5YR 2.5/2	Natural, loamy soil	Gravel (2%), loamy sand, water repellent, 23% C.	Brown Dermosol, non-gravelly, sandy, deep	[e]Eutric Cambisol (Humic)

Where:
[a] Munsell soil colour [36]: measured on the fine earth fraction (<2 mm).
[b] Special-purpose technical soil classification system [27], which uses plain English language places strong emphasis on being either an anthropogenic soil or natural soil, soil texture (e.g. gravelly, sandy, sandy loam) and presence of high amounts of organic carbon (>10%; organic-rich).
[c] Classification of technosols [28]: Connotation: soils dominated or strongly influenced by human-made material; from Greek *technikos*, skilfully made. They contain a significant amount of *artefacts*.
[d] Classification of Anthroposol [28]: Connotation: soils with prominent characteristics that result from human activities; from Greek *anthropos*, human being (e.g. such as addition of organic material and cultivation).
[e] Classification of natural soils: Connotation: soils with substantial soil formation such as Dermosols [29] or Cambisols [28].

Table 2
Summary of soil data using naked eye, image processing, XRD and NDIR analysis of the seven soil types and trace soil transferred to bra fabric [26].

Locality (depth cm)	Centre for Aust. Forensic Soil Science (CAFSS) code	Munsell[1] soil colour <2mm fraction (wet) (dry)	Dominant trace Soil[2] Munsell colour (wet) (dry)	Average soil transferred (individual + aggregates) in pixels[3] (wet) (dry) High quantity / Moderate / Low	Weight % clay content[4] (smectite)	% Organic content[5]	% Gravel content[6]
Soil 1: rose garden path (0-10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	**Reddish gray 2.5YR 6/1** Reddish gray 2.5YR 6/1	**552499** (Moderate) 476907 (Low)	19±3	0.70	90
Soil 2: rose garden path near wall (0-10)	110.6.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	**Light gray 10YR 7/2** Reddish gray 2.5YR 6/1	**551381** (Moderate) 402501 (Low)	15±2	1.21	90
Soil 3: brick fragments (0-2)	110.6.2	**Red 2.5YR 5/8** Light red 2.5YR 7/8	**Reddish gray 2.5YR 6/1** Reddish gray 2.5YR 6/1	**600389** (Moderate) 1305495 (High quantity)	Trace of Mullite	0.29	90
Soil 4: rose garden bed (0-10)	110.7.1	**Black 10YR 2/1** Black 7.5YR 2.5/1	**Dark brown 7.5YR 3/4** Very dark brown 7.5YR 2.5/2	**1271163** (High quantity) 308077 (Low)	2±1	14.0	15
Soil 5: Japanese garden bed (0-10)	110.8.1	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	**Reddish gray 2.5YR 6/1** Reddish gray 2.5YR 6/1	**368712** (Low) 130942 (Low)	2±1	3.10	90
Soil 6: south-east boundary (5-0)	110.9.1	**Leaves** leaves	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**275847** (Low) 87205 (Low)	No XRD analysis	No NDIR analysis	Leaves
Soil 7: south-east boundary (0-10)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	**Dark brown 7.5YR 3/4** Dark brown 7.5YR 3/4	**2154439** (High quantity) 157666 (Low)	20±3	22.8	2

Where: [1] Munsell Soil Colour [34]: measured on the fine earth fraction (<2 mm). [2] Munsell soil colour measured by image processing software from three digital photographs of trace soil on fabric. [3] Average of three STEs tested using either moist or dry soil sample. [4] XRD analysis of % weight clay (Smectite) content in homogenous bulk soil sample. [5] NDIR analysis of organic content of homogenous bulk soil sample. [6] Estimate by naked eye alone using method of McDonald and Isbell [41].

contain a sufficient amount of mineral particles). It was important to have a detailed record of each soil's composition, to ascertain the degree of comparability of these eight soil transfer patterns appearing consistently across all soil types.

2.2. Experimental design

2.2.1. Dragging experiments

The dragging method used was similar to that described by Pounds and Smalldon [20–22] when they tested the transfer and persistence of natural and synthetic yarn fibres to different clothing fabrics. In contrast, experiments in this paper tested the transfer of both wet and dry soil particles to bra fabric. In 84 soil transfer experiments, unpadded, underwire, nylon-elastane bras' DD-cup size provided a large fabric area for experiments; with the opportunity to test how clothing seams effected soil transfer patterns. White fabric enabled easy detection of trace soil transferred. In order to achieve reproducible and consistent results, the weighted fabric was not pushed by hand across the soil tray. This aspect of Pounds and Smalldon's method could not

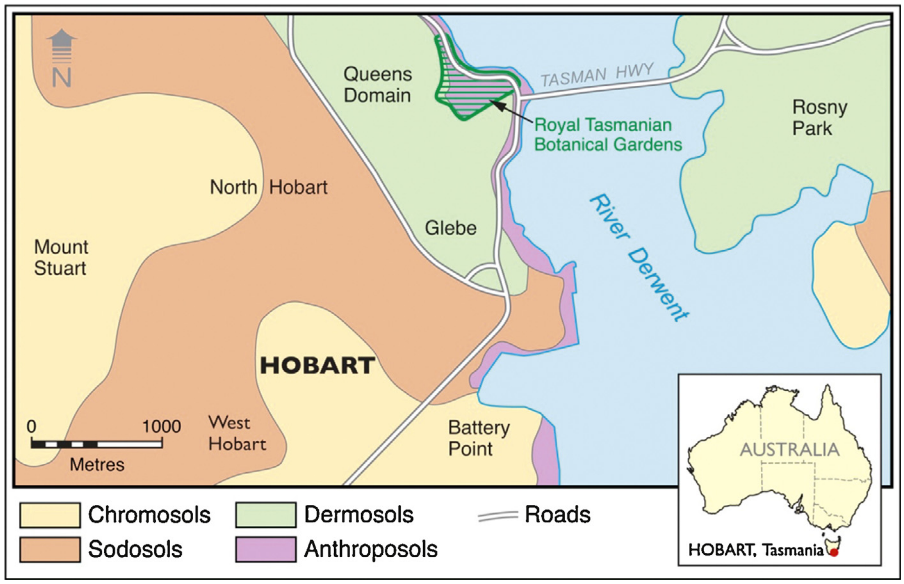

Fig. 1. Soil map showing purple-shaded Anthroposols, which dominate the Royal Tasmanian Botanical Gardens (green cross-hatched area) with minor Dermosols (modified from ASRIS database [32,33] and inset showing the location of Hobart).

replicate a similar amount of force for every pass. Aware of this limitation, they experimented using greater and lesser force to ascertain whether this affected the number of fibres transferred.

To maximise reproducibility of results in these experiments, the weighted fabric was dragged in timed runs across a soil tray using a drag-line (Fig. 3). A smooth-surfaced 2 kg weight, with yellow 'drag line', was enclosed in a tightly fitted plastic bag to enable easy cleaning between STEs.

A glass Pyrex 3 qt/2.8 L dish was filled >3 cm with bulk soil. The non-slip mat and heavy weights on one side ensured the dish did not move during experiments (Fig. 3). The bra-strap or cup was secured firmly to the weight by a strong rubber-band and each bra was manually dragged by a drag-line in timed three second runs through wet or dry soil from one edge of the dish to the other. A metronome set at one second/beat was used to keep the speed of dragging as consistent as possible for all STEs. The attached weight stabilised soil transfer patterns during analysis.

During court proceedings of the aforementioned homicide, it was alleged that a single offender moved the victim's body. It was also alleged that the offender alternated between dragging the victim by both arms and then both legs [1]. To simulate the scenario of a single offender dragging a female victim by either arms or legs, bra-cups and straps were realistically positioned with bra-straps parallel to the direction of movement.

Weighted bras were only dragged in a straight line across the soil dish to maintain a similar distance covered in each STE.

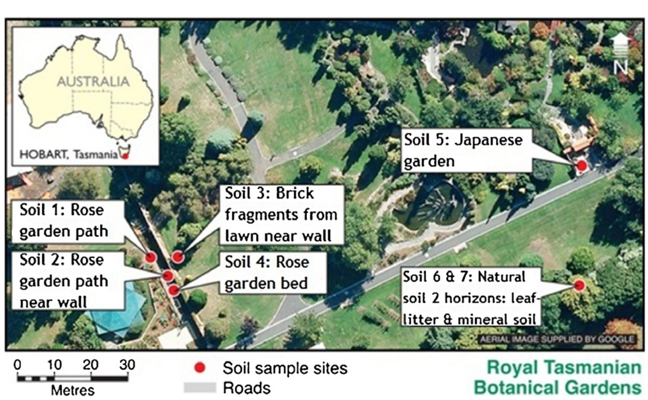

Fig. 2. Aerial photograph showing the distribution of seven soil samples used in STEs, taken from RTBG, Lower Domain Rd, Queens Domain, Hobart. (i) 2 soils taken from Rose Garden Path; (ii) 1 soil taken from lawn at base of Rose Garden Wall; (iii) 1 soil taken from Rose Garden bed; (iv) 1 soil taken from Japanese Garden; (v) 2 soils taken from top two horizons of one soil profile at the Southern fence, Eastern section.

2.2.2. Colour measurement

Munsell soil colour [34] is used in forensic soil analysis to characterise and differentiate soil evidence from different locations. Forensic soil scientists use either naked eye, aided by light microscopy, or expensive spectrophotometers to analyse Munsell colour of soil evidence. The method of trace soil and Munsell soil colour analysis developed in this paper required only a basic computer and image processing software. This method enabled an objective interpretation of Munsell soil colour using digital photographs of trace soil evidence on fabric taken at a crime scene; possibly by a forensic examiner who is not a soil expert.

Munsell soil colour of fine earth (<2 mm) fractions of wet and dry soils was recorded by naked eye in natural daylight (Table 1). This traditional method of soil colour analysis was then objectively compared using image processing analysis. Trimble eCognition Developer image software's default colour system recognised 'Red Green Blue' values in a source digital photograph; but did not recognise Munsell soil colours used by forensic soil scientists [14]. A limited range of 25 Munsell colours was chosen to programme the image processing software; to match and convert 'Red Green Blue' values from digital photographs of trace soil to the Munsell soil colour scheme [26,34].

2.2.3. Recording soil transfer patterns and image processing

In order to simulate the basic equipment available to a crime scene photographer methods and equipment chosen to initially record soil transfer patterns on clothing were kept as simple, portable and inexpensive as possible. The uncontrolled artificial lighting conditions are typical of an indoor crime scene. To be of greatest benefit, this new method needed to be easily understood by police investigators who were not forensic soil scientists. To maintain a pristine record of trace soil patterns on fabric, this forensic soil evidence would need to be recorded at the crime scene, before the body was moved or clothing removed.

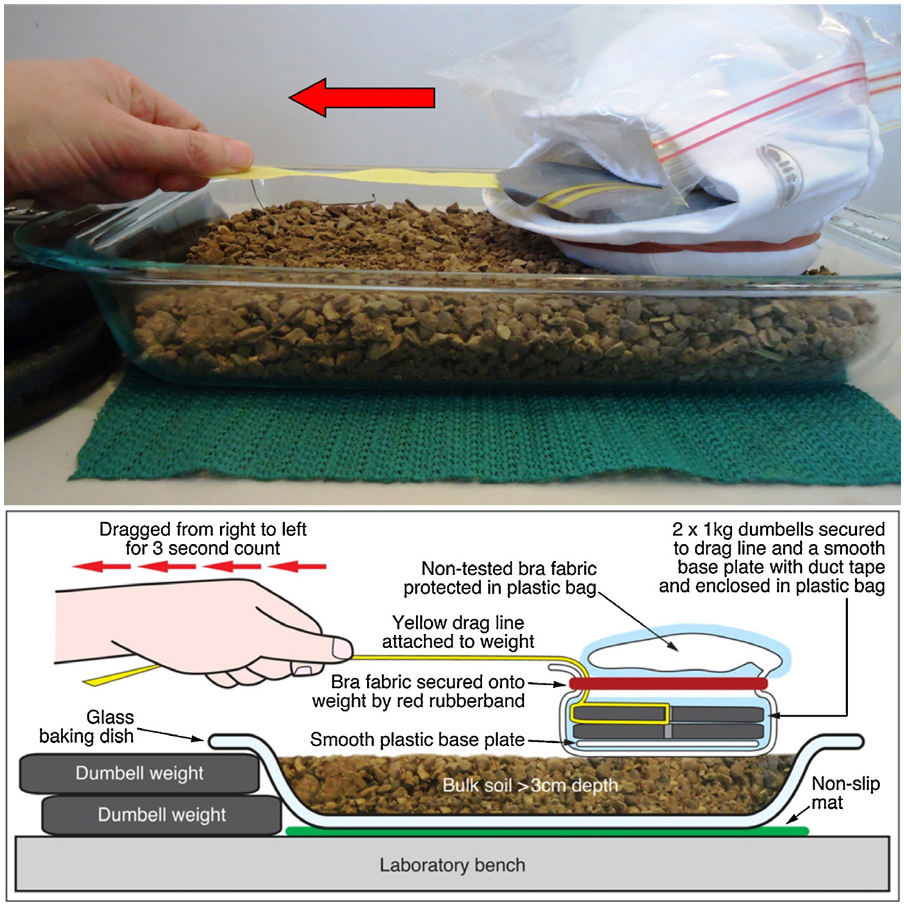

Fig. 3. Photograph (1) and cross-section (2) of weighted bra dragged from right to left over soil material during a three second count Soil Transference Experiment (STE). Sections of bra not currently tested for dragging over soil remained clean inside the plastic bag on top. The glass dish containing soil was on a nonslip mat with a backstop of weights on the left to prevent movement during the STE.

There was also an underlying intention to develop an inexpensive and easily accessible method of forensic soil analysis that could be adopted by police and forensic scientists in developing nations.

Digital photography using a basic digital camera was therefore chosen as the preferred method of recording soil transfer patterns on fabric. STEs were photographed under artificial lighting and not moved into natural sunlight for photographing, as recommended by Munsell [34].

The entire fabric surface dragged across soil was photographed by a Sony Cyber-shot DSC-W530 14.1 megapixel camera, under artificial lights in the laboratory. Photographs were taken of each soil transfer pattern with the weight still attached; to record the pattern in a pristine state. The influence of artificial lighting on image processing Munsell colour analysis was minimised by using the white scale bar as a colour standard [26]. Trace soil transferred onto 21 bras and bulk soil samples taken from RTBG were examined under a low-powered binocular WILD Heerbrug M5-53707 microscope. Digital photomicrographs were taken with a Leica DFC-425 and the Leica Application Suite, Version 3.6.0.

Trimble eCognition Developer image processing software analysed one digital photo per STE; which were combined by soil sample and moisture content to produce Excel graphs. This software enabled soil transferred to fabric to be identified by determining the number of fabric pixels (minimum 2 pixel/soil object) in each digital photograph covered by soil. Soil transferred to bra-straps did not undergo image processing. Bra-cups provided a larger fabric area for analysis.

Image processing of photographs of the trace soil patterns on fabric was used to: (i) confirm patterns observed visually by human eye, (ii) provide standardised numerical data of the colour and shape of soil objects ≥100 μm/2 pixel and (iii) allow statistical comparison of observed soil patterns. This included quantity and directionality of soil transferred, percentage of individual soil objects and aggregates and Munsell soil colour range.

Image processing data on directionality were entered into GEOrient version 9.5.0 [35] to produce Rose Diagrams of trace soil patterns for quick and clear comparisons.

Limitations in software programming were overcome by disregarding soil objects <100 μm. Difficulties differentiating mineral from organic soil objects could feasibly be overcome with more complex programming.

3. Results

3.1. Trace soil patterns documented on fabric using transfer method of 'dragging'

The following eight (8) transfer patterns were seen across all 7 soils tested; but only the first six occurred with 100% consistency [26] in this dragging experiment:

(1) Soil 'trails' were observed by naked eye on the bra-straps and cups as a result of soil transported across the fabric parallel to the direction of movement (see red circles in Fig. 4(1)–(4)). The

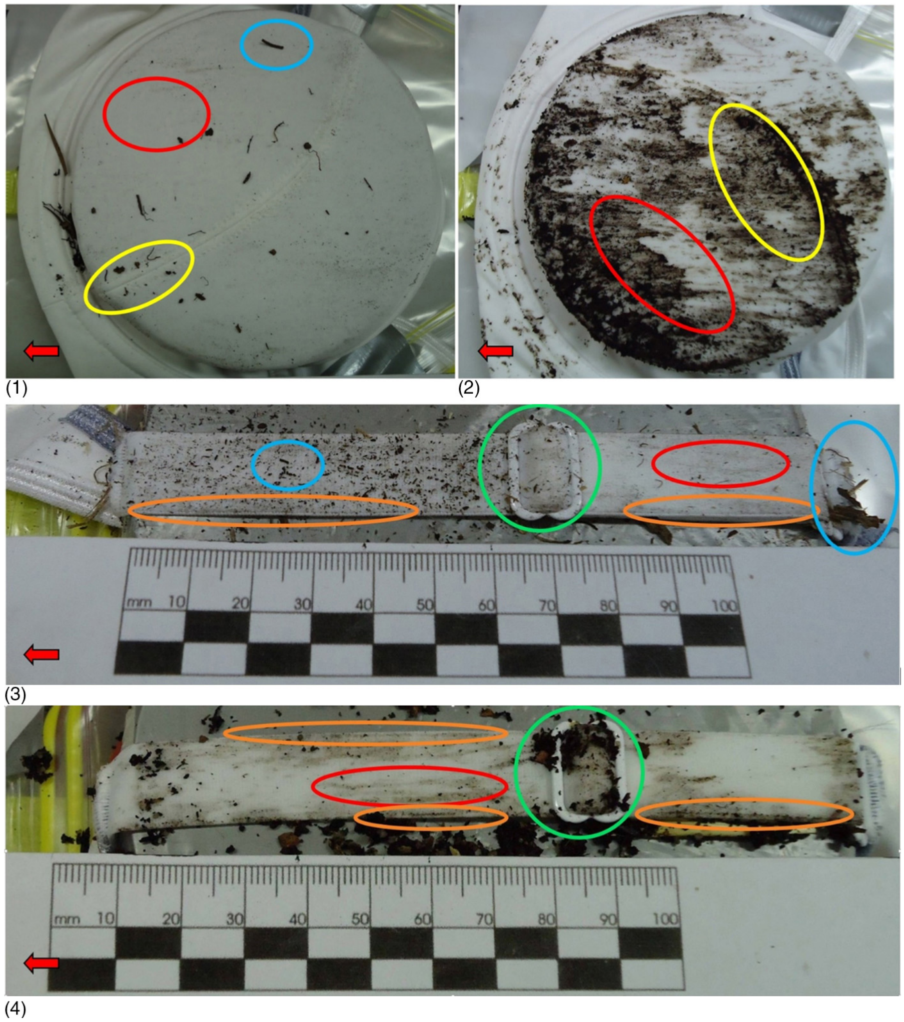

Fig. 4. Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing either wet or dry soil (Direction of movement = right to left). (1) DRY Natural loamy soil (Soil 7: underlying mineral soil) (2) WET natural loamy soil (Soil 7: underlying mineral soil) (3) DRY anthropogenic, organic-rich sandy loam soil (Soil 4: Rose garden bed) (4) WET Anthropogenic, organic-rich sandy loam soil (Soil 4: Rose garden bed).

darker colour of wet soil contrasted more strongly against the white fabric compared to dry soil; and a greater quantity of wet soil was transferred than dry.

(2) Soil accumulated intermittently along the edges of shoulder-straps in all STEs (see orange circles Fig. 4(3) and (4)). This indicated not only that fabric was dragged, but that direction of movement was parallel to the bra-strap during transfer.

(3) Soil objects accumulated in front and on top of raised middle seams in all bra cups, at an angle to the direction of motion; regardless of soil moisture content. Soil transference was minimal directly behind the raised seam; indicating direction of movement (see yellow circles in Fig. 4(1) and (2)).

(4) Likewise, soil accumulated on the metal bra-strap buckle and on strap fabric in front of the leading edge of the metal bra-strap buckle, when the strap was dragged across soil. This provided an indicator of direction (see green circles in Fig. 4(3) and (4)). This soil could be seen by naked eye alone, except when wet soil had minimal clay content; as occurred with 90% quartz gravel (Soil 5: Japanese garden bed) and soil composed entirely of undecomposed leaves (Soil 6: surface natural organic-rich leaves) (Fig. 5(1) and (2)) These exceptions are discussed in greater detail in pattern (6) below.

(5) When the weighted bra was dragged across dry soil, very dry clay-sized particles 'dusted' or speckled the metal bra-strap buckle evenly like icing sugar (see green circle in Fig. 4(3)).

(6) Wet soil left metal bra-strap buckles wet and shiny, often with 1–2 mm muddy clumps transferred onto an otherwise shiny clean surface; to an extent dependent on soil type (see green circle in Fig. 4(4)). This contrasted with dry soil runs, where the speckled surface produced an all-over matt appearance on the metal buckle. Occasionally, these tiny clumps had their own microscopic soil 'trails' [26]. Metal buckles dragged through soil with negligible clay-sized content (Soil 5: Japanese garden bed and Soil 6: surface natural organic-rich leaves) appeared shiny clean with a few water droplets remaining. However, using light microscopy, water droplets were clouded with extremely fine soil particles (see purple circles Fig. 5(1) and (2)).

(7) Regardless of moisture content, elongated particles of soil material such as grass seeds, dry grass or wood debris $\geq$2 mm), aligned parallel with direction of movement. This pattern was not consistent throughout all STEs, occurring on average 65% using seven soils tested (see blue circles in Fig. 4(2) and (3))

(8) Soil accumulated in fluffy raised seams at the ends of bra straps. This occurred in only 47% of dry soil STEs and 28% of wet soil STEs (see blue circle at far right of bra strap in Fig. 4(3)).

3.2. Mineralogy and organic carbon

Murray et al. [26] compared the effect of soil mineralogy on resulting transfer patterns using powder X-ray diffraction [36–38].

Fig. 5. Photomicrographs of trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing either wet or dry soil. (1) WET Anthropogenic, quartz-rich gravelly sandy soil (Soil 5: Japanese garden bed) (2) WET natural organic-rich soil (Soil 6: surface natural organic-rich leaves).

If soils tested were vastly different in mineralogical composition, this might imply a 'universality' to transfer patterns seen across all soils tested. Thirteen (13) minerals typical of loamy-to-clayey Tasmanian soils were identified [26].

The two Anthropogenic, gravelly sandy loam soils (Soils 1 and 2) from the Rose Garden Paths with 15–19% clay also included of 90% sandstone and mafic igneous gravel but with negligible organic matter (i.e. as measured organic carbon content in Table 1). Mineralogical composition was approximately 40% weight of quartz, with 20% of both plagioclase and smectite clay. The natural loamy soil (Soil 7: underlying mineral soil) had a similar amount of clay (20%), quartz and smectite clay content to Rose Garden Path soils, but differed with its high organic content of 38% weight.

The Anthropogenic, organic-rich sandy loam soil (Soil 4: Rose garden bed) was 69% weight quartz with organic content of 24%. In contrast, the Anthropogenic, quartz-rich gravelly sandy soil (Soil 5: Japanese garden bed) had high quartz content (83%), minimal clay or organic content. The Anthropogenic, brick fragment-rich soil had high quartz content, with negligible organic content and traces of mullite, calcite, rutile and hematite. The greatest differences between soils were the carbon levels; ranging from 0.26% to 3.10% in the gravel-rich anthropogenic soils. In contrast, 14% carbon was measured in the Anthropogenic, organic-rich sandy loam soil (Soil 4: rose garden bed) and 22.8% carbon in the natural loamy soil (Soil 7: underlying mineral soil) (Table 1). Low sulfur contents were measured but no sulfur-bearing minerals were identified; generally correlating sulfur with organic matter. Smectite and organic content of each soil sample is reported in Table 2.

3.3. Munsell soil colour range of soil transferred to fabric in pixels

A graphic display of Munsell colour ranges identified for every STE revealed image processing could identify a set of Munsell colours, unique to a soil sample's location. Full results are available in Murray et al. [26]; detailing the Munsell colour ranges identified by image processing software for every individual STE, as well as graphs combining results by soil type and moisture content.

Minor discrepancies between dominant and subdominant Munsell colour peaks chosen by naked eye and image processing software did occur; possibly due to limitations in programming adjustments between artificial and natural lighting. For example, fine earth (<2 mm) fractions of the two Anthropogenic, gravelly sandy loam soils (Soils 1 and 2) from the Rose Garden Paths, under natural daylight by naked eye, showed a Munsell colour of 7.5YR 5/2 when dry and a darker 7.5YR 3/2 when wet (Table 1). However, dry trace soil on fabric photographed under artificial lighting was analysed by image processing software as displaying a dominant colour of 2.5YR 6/1; with minor peaks at 7.5YR 2.5/2, 5.2 and 10YR 6/3 and 7/2. When wet, trace soil displayed three dominant Munsell colour peaks at 2.5YR 6/1, 10YR 6/3 and 7/2; with minor peaks at 7.5YR 2.5/2 and 5/2 (Fig. 6).

The colour range chosen by image processing often had similar dominant and subdominant peaks throughout six individual trace soil patterns originating from one soil location. The consistency of image processing Munsell colour results were documented using very similar soil taken from four metres apart on the Rose Garden Path. Wet and dry Anthropogenic, organic-rich sandy loam soil (Soil 2: Rose garden bed near wall) under natural daylight by naked eye, showed the same fine earth fraction Munsell colours as the Anthropogenic, organic-rich sandy loam soil (Soil 1: Rose garden bed) (Table 1).

Image processing recorded Munsell colour of dry trace soil on fabric with dominant peaks at 2.5YR 6/1 and 7.5YR 2.5/2; with minor peaks at 7.5YR 5/2 and 10YR 6/3. When wet, dominant peaks were identified at 2.5YR 6/1, 10YR 6/3 and 7/2 (Fig. 6). Minor peaks clustered at 7.5YR 2.5/2, 3/4, 4/6 plus 10YR 5/3.

When results from these twelve STEs were graphed separately, image processing consistently identified very similar dominant and subdominant peaks in specific Munsell colours over a limited range of 25 Munsell colours. Using digital photographs of trace soil on clothing alone, twelve items of clothing out of eighty-four were correctly linked to trace soil originating from the Rose Garden Path [26].

3.4. Directionality

Often it is desirable to present orientation data in such a way that the distribution of orientations is emphasised independently of the geographic location of data; such as whether there is a pattern of preferred orientation of the soil patterns in an area on the bras. The types of diagrams most frequently used to present such information are histograms, rose diagrams and spherical projections [39]. Rose diagrams are essentially histograms for which the orientation axis is transformed into a circle to give a true circular plot. They are commonly used in structural geology to plot the orientation of joints and dykes. Wind directions and frequencies are also plotted on rose diagrams.

Using the image processing directional or orientation data, rose diagrams [35] mapped the orientation of thousands of dry or wet soil particles displayed as $\geq$2 pixels diameter transferred onto fabric (Fig. 7). Strong uni-modal directionality was displayed when fabric was dragged in one direction across soil. On the rose diagrams, black directional lines reached the edges of the rose diagram in a distinctly horizontal line. This concurred with source digital photographs of trace soil on fabric photographed with soil trails across fabric positioned horizontally.

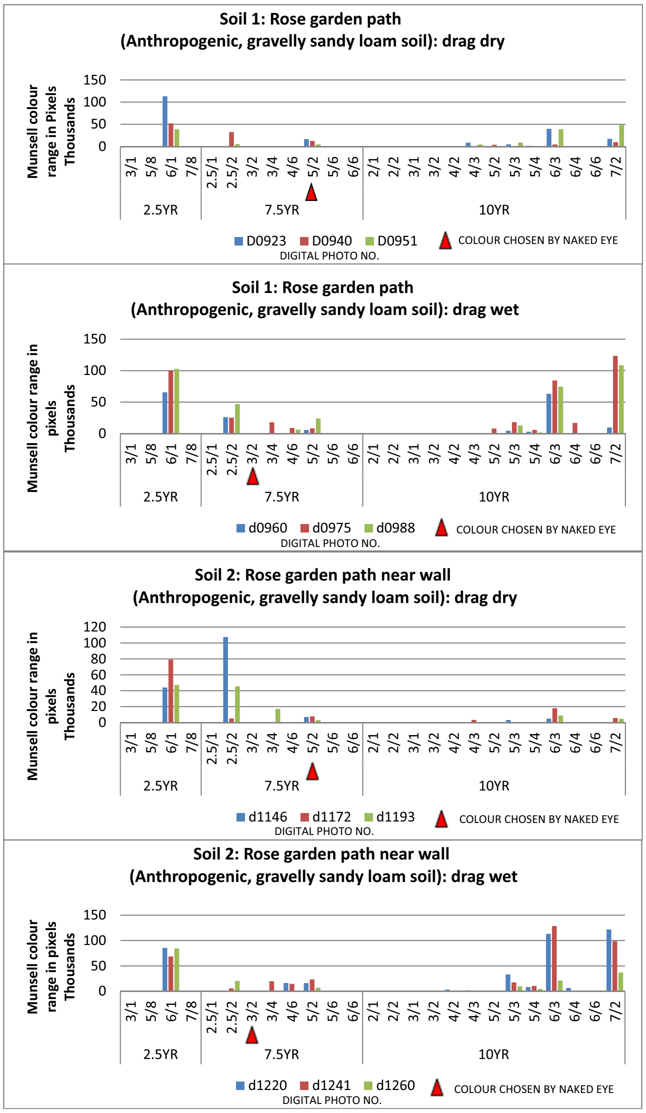

Fig. 6. Munsell soil colour ranges recognised by image processing software from Soil 1 (Rose Garden Path) and Soil 2 (Rose Garden Path near wall) transferred onto fabric when dry and wet. Numerical data from three digital photographs are combined in each graph.

Dry soil objects tended to gather against the bra's perpendicular middle seam; producing greater bi-modal directionality. Dry soil had more individual soil objects, which would scatter randomly over fabric. During STEs using soil with 90% white gravel from the Anthropogenic, quartz-rich gravelly sandy soil (Soil 5: Japanese garden bed) and the Natural organic-rich soil (Soil 6: surface natural organic-rich leaves) with negligible mineral content, minimal trace soil was transferred to bra fabric. Image processing still managed to quantify these minute soil traces, to create Rose Diagrams displaying strong uni-modal directionality.

3.5. Quantity of soil transferred to fabric analysed by soil type

Quantity of soil transferred to fabric was measured by image processing analysis using digital photographs taken of each STE. Image processing of digital photographs taken of soil transferred onto fabric provided an objective approach to graphically present soil transfer patterns. Quantitative graphical presentation of soil patterns, including texture, mineralogy, chemistry, moisture content, quantity and directionality of soil transferred, added standardised objectivity not possible through identification by naked eye alone. Image processing numerical data is summarised in Table 2 and Fig. 8. Computer analysis of the number of digital pixels, containing either individual or aggregate soil objects, provided a level of accuracy impossible by naked eye examination.

Soils were grouped by location and soil moisture content. Numerical data for individual and aggregate soil objects transferred from each soil sample to fabric, were combined and averaged.

Soil objects covering >0.5 million pixels were classified as being a low quantity of soil transferred to fabric.

Soil objects covering 0.5 million to >1 million pixels were classified as a moderate quantity of soil transferred.

Soil objects covering 1 million pixels and higher were classified as a high quantity of soil transferred.

Using image processing numerical data that measured the quantity of soil objects (both individual and aggregates) transferred to fabric, the following associations between soil types, clay mineral properties (smectite) and soil moisture content was discovered:

- Anthropogenic, gravelly sandy loam soil (Soil 1 and 2: Rose Garden Paths; Table 2) with low organic carbon content, produced a low-moderate quantity of reddish gray soil objects when transferred to the fabric when dry and increasing to moderate quantity when wet (reddish to light gray).
- Anthropogenic brick fragment-rich soil (soil 3: brick fragments) with high quartz and negligible organic and smectite content, produced a high quantity of reddish gray soil objects when transferred to the fabric when dry, decreasing to moderate quantity when wet (reddish gray).
- Anthropogenic, organic-rich sandy loam soil (Soil 4: Rose garden bed) with approximately 15 to 19% smectite and high amounts of arkosic sandstone and andesitic-to-weathered mafic igneous rock produced a low to moderate quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to a high quantity when wet (dark brown).
- Anthropogenic, quartz-rich gravelly sandy soil (Soil 5: Japanese garden bed) with high quartz content and negligible organic and smectite content, produced a trace reddish gray coloured soil transference pattern to fabric when dry, increasing to a low quantity when wet (reddish gray).
- Natural organic-rich soil (Soil 6: surface natural organic-rich leaves) with very high organic carbon content, produced a trace quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to low quantity when wet (very dark brown).
- Natural loamy soil (Soil 7: underlying mineral soil) with approximately 20% smectite produced a moderate quantity of dark brown soil objects when transferred to the fabric when dry and increasing to high quantity when wet (dark brown). This is because smectite is highly responsive to soil moisture and soils with high smectite content can undergo as much as a 30% volume change; an indication of smectite's shrink/swell potential [40]. This characteristic of smectite clay may help explain the distinctly observable differences seen in trace soil patterns when dry or wet soil was transferred to fabric.

In summary, both the Rose Garden Path soils (Soils 1 and 2) and the natural loamy soil (Soil 7: Underlying mineral soil) contained smectite between 15 and 20%. A greater quantity of soil objects from these two soil types, in particular soil aggregates, were transferred to fabric when these soil types were wet (Table 2; Figs. 4(1) and (2) and 8). Soil aggregates made up approximately two-thirds of all soil objects detected by image processing. Dry soil samples produced the largest percentage of individual soil objects

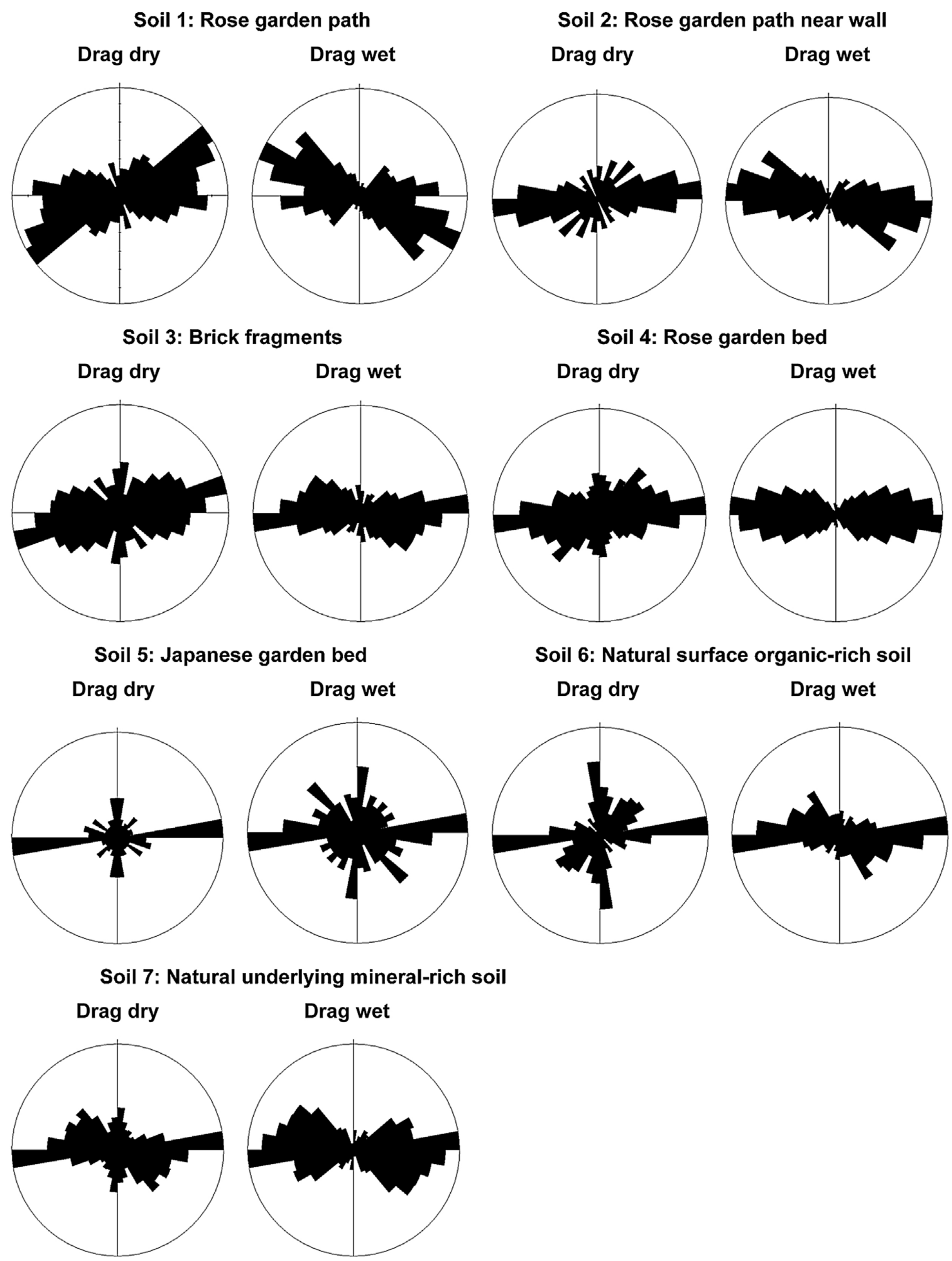

Fig. 7. Rose diagrams of the directionality of dry and wet soil transferred onto fabric. Strong uni-modal directionality was produced when fabric was dragged right to left across soil. Dry soil particles more than set soil tended to gather against the middle seam, creating more bi-modal directionality.

transferred per area of fabric; with wet soil producing a greater percentage of aggregates [26].

4. Discussion

Most soil particles transferred to fabric in STEs were very fine silt or clay-sized fragments [16]. The largest fragment transferred was a 5 mm × 4 mm brick fragment [26]. When removing the 2 kg weight used to stabilise the fabric surface and maintain optimum contact with the soil surface during each STE, larger (>0.5 cm) loose soil objects were easily dislodged; accumulating in the storage bag. Whereas fine fractions transferred in soil trails tended to remain 'in situ'; half-embedded in fabric.

All soil textures tested (loamy-sand, sand, brick or undecomposed leaves in Table 2) produced soil transfer patterns to a greater or lesser extent. Soils with higher clay content increased quantity and persistence of soil particles transferred. Fine clay-sized particles showed greatest adherence or persistence on fabric regardless of soil moisture [42]. Persistence of clay particles increased when moisture enabled clay objects to coat or impregnate fabric fibres; also acting as 'mortar' to secure larger grains or stabilise soil aggregates.

The least consistent transfer pattern, an 'alignment' of elongated particles with direction of drag, should not be relied upon to interpret transfer method in the field; unless elongated particles (such as grass seeds or twigs) are actually pushed under or embedded in the fabric.

4.1. Image processing of soil transfer patterns on fabric

Because photographs of trace soil patterns were taken using a very basic 14.1 megapixel digital camera under artificial lighting in

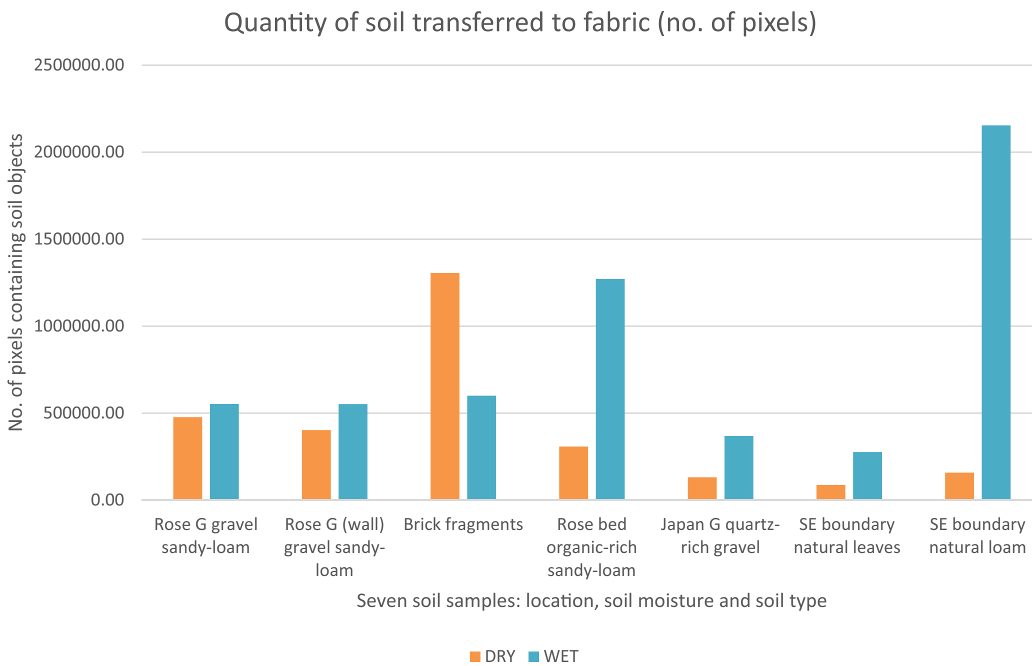

Fig. 8. Quantity of soil transferred to fabric, analysed by number of pixels in digital photographs that contained individual or aggregate soil objects. Image processing numerical data is subdivided by location and soil moisture content [26].

the laboratory, it was correctly predicted that initial Munsell colours chosen for soils by naked eye in natural daylight would differ from those detected by image processing software.

Despite the limitations of these source photographs, image processing chose the same colour for the dry Anthropogenic, quartz-rich gravelly sandy soil (Soil 5: Japanese garden bed). The dry natural loamy soil (Soil 7: underlying mineral soil) had a semi-dominant peak of the same Munsell colour chosen under natural daylight. The dry anthropogenic, gravelly sandy loam soil (Soil 1: Rose Garden Path) was only one Munsell colour shade different than the initial Munsell colour chosen for dry fine soil fraction under natural daylight. When Munsell colour results are so close, the variability of the human retina must also be considered.

Only the natural loamy soil (Soil 7: underlying mineral soil) produced clusters of neighbouring Munsell colours in dry and wet trace soil transferred. Other soils produced more distant Munsell colour peaks.

Not only did image processing software create a range of Munsell colours using photographs of trace soil on fabric, the same range of Munsell colours was correctly identified from trace soil on twelve different bras; linking this trace soil 'evidence' to the Rose Garden Path. Using two soils sampled only four metres apart, image processing matched the same dominant peaks of Munsell colours in both dry and wet trace soil on fabric.

Comparing graphs of image processing numerical data of all soil samples revealed this software identified the same range of specific Munsell colours in individual photographs of STEs [26]. The power of image processing to identify Munsell colour ranges to link trace soil on clothing to a specific location may prove as integral to forensic soil investigation as XRD's ability to identify peaks of soil minerals.

4.2. Potential application of image processing for soil evidence

Image processing analysis of crime scene photographs may enable trace soil on clothing and possibly shoe and tyre treads to be compared by Munsell colour. The same colour standard, such as a white scale bar, would allow photographs taken under differing lighting conditions or using different cameras to be compared. This new method of trace soil colour analysis could include all 450 standard Munsell colour chips for crime scene analysis; without requiring a spectrophotometer. Image processing of digital trace soil photographs may become a preliminary step to compare and contrast different soil evidence before more expensive and time-consuming analytical testing occurs; such as XRD analysis of soil mineralogy. This initial step may mean vital forensic soil evidence is not completely ignored due to massive backlogs of evidence in major laboratories.

After several days of programming image processing software to identify soil objects on fabric, analysis of each digital photograph took only minutes to produce a quantifiable graphical presentation. Simple Excel graphs made comparison of STEs easy to comprehend.

A valuable outcome was the application of image processing software to produce Rose diagrams plotting directionality of trace soil transferred onto fabric. All digital photographs were taken of soil transfer patterns, with the direction of movement running horizontally from right to left. This aided recognition of soil transfer patterns that were being documented for the very first time; and resulted in digital photographs with all soil 'trail' patterns running horizontally. Rose diagrams accordingly indicated strong uni-modal horizontal directionality; even with minimal trace soil amounts. However, dry soil objects tended to be 'dammed' against the perpendicular middle seam during dragging experiments; created bi-modal directionality in some rose diagrams.

Combining image processing with rose diagrams objectively proved directional patterns recognised by naked eye could also be identified by computer software. The current forensic soil techniques utilising light microscopy, XRD and Scanning Electron Microscopy [43,44], could include image processing of trace soil patterns on clothing or other fabrics.

XRD analysis is used routinely to identify mineral composition of trace soil on clothing. In cases where soil evidence from multiple locations share very similar mineralogy, image processing using digital photographs could be used in conjunction with XRD, to provide an objective, accurate and detailed method to compare and contrast soil evidence by colour alone.

The standardised objectivity achieved by combining these techniques, could not only assist forensic investigators understand the circumstances behind fabric making contact with a soil surface, but gain acceptance of this evidence beyond reasonable doubt in a court of law.

These STEs can only indicate potential soil transfer patterns when a clothed victim is dragged across soil. They cannot indicate other modes of transfer, such as placing a clothed victim on soil or a combination of several methods. Alternative methods of soil transfer to fabric, suggested during court proceedings in the aforementioned Australian homicide [1,2,4], shall be explored in depth in future papers.

5. Conclusions

Laboratory STEs used the transfer method of dragging weighted clothing (bras) across wet and dry RTBG soils. Digital photography taken immediately after each STE provided a pristine record of soil transference patterns on clothing fabric before each bra was removed from the stabilising 2 kg weight.

Eighty four (84) soil transfer experiments undertaken on 5 anthropogenic and 2 natural soils from the Royal Tasmania Botanic Gardens produced eight patterns identified by naked eye and confirmed by light microscopy and image processing. Only the first six patterns were seen with the naked eye with 100% consistency [26].

Soils were further categorised by compositional characteristics into six different soil types, both natural and anthropogenic. Soil transfer patterns were then investigated to determine the most influential factors that characterised the composition of the source soil. Quantity of soil transferred was dependant primarily on soil type, moisture content, particle size and mineralogy. Dark organic loamy sand textured soil provided the most abundant and easy to identify soil transfer patterns against the white bra fabric. Gravel-rich, matrix-poor and low-clay soils transferred the lowest quantity of soil to fabric.

Image processing software proved valuable in providing quantifiable graphical presentations on:

(i) quantity of soil transferred, (ii) percentage of individual soil objects and aggregates transferred and (iii) direction patterns and (iv) the ability to identify and compare Munsell colours.

Dragging was the only transfer method tested and underlying fabric was smooth-textured, white and non-patterned, to better enable trace soil transferred to be identified by image processing software. Future experiments will need to be conducted using different transfer methods to identify whether any soil transfer patterns on fabric are so unique that they can be used to indisputably identify a specific transfer method. Future programming of image processing software will need to focus on enabling differentiation of underlying fabric colours, patterns or textile textures from trace soil transferred. If this method of forensic soil analysis became accepted, a scale bar with a white colour standard may be developed to assist with image processing software calibration and improve Munsell soil colour recognition using digital photographs of trace soil evidence.

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References

[1] B. Martin, The State of Western Australia v. Rayney. [No 3]: WASC, 2012, 1–369.
[2] B. Martin, Judgement Summary: The State of Western Australia v. Rayney. [No 3]: WASC, 2012, 1–13.
[3] R. Fitzpatrick, M. Raven, P. Self, Detailed mineralogical characterization of small brick and soil fragments (<0.5 mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to operation Dargan, in: Centre for Australian Forensic Soil Science Restricted Client Report, 2011, 1–116.
[4] R. Fitzpatrick, M. Raven, The State of Western Australia v. Lloyd Patrick Rayney Trail: Request for Supplementary Statement Relating to Extraction of Particulate Material from Bra, Centre for Australian Forensic Soil Science, 2012, pp. 1–17.
[5] R. Fitzpatrick, M. Raven, How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists, Soil Horiz. 53 (2012) 14–29, http://dx.doi.org/10.2136/sh12-05-0016.
[6] R. Fitzpatrick, M. Raven, S. Forrester, 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, Springer Netherlands, Netherlands, 2009, pp. 105–127, http://dx.doi.org/10.1007/978-1-4020-9204-6_8.
[7] R. Fitzpatrick, M. Raven, Soils, in: J. Siegel, P. Saukko (Eds.), Encyclopedia of Forensic Sciences, 2nd ed., Academic Press, Waltham, MA, 2013, pp. 206–212, http://dx.doi.org/10.1016/B978-0-12-382165-2.00113-6.
[8] R. Fitzpatrick, Soil: forensic analysis, in: A. Jamieson, A. Moenssens (Eds.), Wiley Encyclopedia of Forensic Science, Chichester, West Sussex, 2013, http://dx.doi.org/10.1002/9780470061589.fsa096.pub2.
[9] R. Murray, Evidence from the Earth: Forensic Geology and Criminal Investigation, 2nd ed., Mountain Press Publishing, Missoula, MT, 2011.
[10] K. Pye, Geological and Soil Evidence: Forensic Applications, CRC Press, Boca Raton, FL, 2007.
[11] A. Ruffell, J. McKinley, Geoforensics, John Wiley & Sons, Ltd, Chichester, 2008.
[12] R. Morgan, P. Bull, Forensic geosciences and crime detection: identification, interpretation and presentation in forensic geoscience, Minerva Medicolegale 127 (2007) 73–89.
[13] P. Bull, A. Parker, R. Morgan, The forensic analysis of soils and sediment taken from the cast of a footprint, Forensic Sci. Int. 162 (2006) 6–12, http://dx.doi.org/10.1016/j.forsciint.2006.06.075.
[14] R. Sugita, Y. Marumo, Validity of color examination for forensic soil identification, Forensic Sci. Int. 83 (1996) 201–210, http://dx.doi.org/10.1016/S0379-0738(96)02038-5.
[15] S. McDermott, Trace evidence: transfer, persistence and value, in: J. Siegel (Ed.), Encyclopedia of Forensic Sciences, 2nd ed., Academic Press, Waltham, 2013.
[16] P. Bull, R. Morgan, A. Sagovsky, G. Hughes, The transfer and persistence of trace particulates: experimental studies using clothing fabrics, Sci. Justice 46 (2006) 185–195, http://dx.doi.org/10.1016/S1355-0306(06)71592-1.
[17] K. Aardahl, S. Kirkowski, R. Blackledge, A target glitter study, Sci. Justice 45 (2005) 7–12, http://dx.doi.org/10.1016/S1355-0306(05)71615-4.
[18] K. Aardahl, Evidential Value of Glitter Particle Trace Evidence, National University, San Diego, CA, 2003.
[19] T. Hicks, R. Vanina, P. Margot, Transfer and persistence of glass fragments on garments, Sci. Justice 36 (1996) 101–107, http://dx.doi.org/10.1016/S1355-0306(96)72574-1.
[20] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part I: fibre transference, J. Forensic Sci. Soc. 15 (1975) 17–27, http://dx.doi.org/10.1016/S0015-7368(75)70932-5.
[21] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part II: fibre persistence, J. Forensic Sci. Soc. 15 (1975) 29–37, http://dx.doi.org/10.1016/S0015-7368(75)70933-7.
[22] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. III: a preliminary

investigation of the mechanisms involved, J. Forensic Sci. Soc. 15 (1975) 197–207, http://dx.doi.org/10.1016/S0015-7368(75)70985-4.
[23] C. Roux, J. Robertson, Fibers, in: J. Siegel (Ed.), Encyclopedia of Forensic Sciences, 2nd ed., Academic Press, Waltham, MA, 2013.
[24] E. Locard, Analyses of dust traces parts I, II and III, Am. J. Police Sci. 1 (1930) 276–298 (401-18, 96-514).
[25] R. Morgan, J. Cohen, I. McGookin, J. Murly-Gotto, R. O'Connor, S. Muress, et al., The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence, Sci. Justice 49 (2009) 277–285, http://dx.doi.org/10.1016/j.scijus.2009.02.004.
[26] K. Murray, R. Fitzpatrick, R. Bottrill, R. Berry, R. Woolley, R. Doyle, et al., Soil Patterns on Bra Fabrics Dragged Across Different Soil Surfaces Using Image Analyses: Laboratory Dragging Experiments. Acid Sulfate Soils Report No ASSC_096, The University of Adelaide, Adelaide, Australia, 2015, pp. 1–100, http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=34394;m=view.
[27] R. Fitzpatrick, Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use, in: F. Taha, M. Abdelfattah (Eds.), Developments in Soil Classiification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources, Springer, Netherlands, 2013, pp. 51–83, http://dx.doi.org/10.1007/978-94-007-5332-7_2.
[28] IUSS_Working_Group_WRB, World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106, FAO, Rome, 2014, pp. 1–181, http://www.fao.org/3/a-i3794e.pdf.
[29] R. Isbell, The Australian Soil Classification, Revised ed., CSIRO Publishing, Melbourne, 2002.
[30] D. Reid, Unpublished Statement from RTBG Horticultural Coordinator, Regarding the Establishment of the Gardens and the Heritage-Listed Convict-Built Eardley Wilmot Brick Wall, 2012.
[31] Soil_Survey_Staff, Keys to Soil Taxonomy, 12th ed., United States Department of Agriculture, Natural Resources Conservation Service, Washington, DC, 2014.
[32] ASRIS (Australian Soil Resources Information System), Maps, ASRIS (Australian Soil Resources Information System), (Database), CSIRO Land and Water, Canberra, ACT, Australia, 2013.
[33] D. Leaman, Hobart, in: D. Leaman (Ed.), Geological Atlas 1:50 000 Series, Geological Survey Tasmania, Tasmania, Australia, 1976 (Sheet 82 (8312S)).
[34] Munsell_Color_Company, Munsell Soil Color, Book, Munsell Color X-rite, Michigan, 2009.
[35] R. Holcombe, GEOrient, School of Earth Sciences, University of Queensland, Queensland, Australia, 2011, http://www.holcombe.net.au/software/rodh_software_georient.htm.
[36] F.H. Chung, Quantitative interpretation of X-ray diffraction patterns of mixtures. III. Simultaneous determination of a set of reference intensities, J. Appl. Crystallogr. 8 (1974) 17–19.
[37] P. Maniar, G. Cooke, Modal analyses of granitoids by qualitative X-ray diffraction, Am. Mineral. 72 (1987) 433–437.
[38] H. Klug, L. Alexander, X-ray Diffraction Procedures for Polycrystalline and Amorphous Materials, Wiley, New York, NY, 1954.
[39] A. Allaby, M. Allaby, A Dictionary of Earth Sciences, Oxford University Press, 1999.
[40] C. Weaver, Clays, muds and shales, in: C. Weaver (Ed.), Developments in Sedimentology, Elsevier, Amsterdam, 1990.
[41] R. McDonald, R. Isbell, Soil Profile, 3rd ed., CSIRO Publishing, Melbourne, 2009.
[42] R. Fitzpatrick, M. Raven, P. Self, Clay mineralogy as significant evidence in 4 murder investigations involving a wide range of earth materials from Perth, Adelaide, Melbourne and Sydney, in: R.J. Gilkes (Ed.), Proceedings 23rd Australian Clay Minerals Society Conference, Australian Clay Minerals Society, Perth, 2014, pp. 23–26.
[43] W. Pelton, Use of SEM in textile forensic work, in: J. Hearle, B. Lomas, W. Cooke (Eds.), Atlas of Fibre Fracture and Damage to Textiles, Woodhead Publishing Limited, Cambridge, 1998, pp. 406–415.
[44] W. Pelton, Distinguishing the cause of textile fibre damage using the scanning electron microscope (SEM), J. Forensic Sci. 40 (1995) 874–882, http://dx.doi.org/10.1520/JFS15401J.

3. CHAPTER 3 Patterns produced when soil is transferred to bras by placing and dragging action: the application of digital photography and image processing to support visible observations

This chapter tests whether the soil transfer patterns documented when a simulated clothed human body is dragged across a soil surface under controlled laboratory conditions, can also be identified at a simulated crime scene in the field. A new soil transfer method of placing a replica clothed human body on a soil surface is also tested. The resulting sets of transfer patterns are then compared to ascertain whether there are distinct differences that could be used in a forensic investigation to differentiate methods of soil transfer using trace soil on clothing.

The method of combining digital photography with image processing is used to objectively compare numerical data taken from both soil transfer methods of dragging and placing weighted fabric on a soil surface.

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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

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iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Patterns produced when soil is transferred to bras by placing and dragging actions: The application of digital photography and image processing to support visible observations

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ABSTRACT

A series of soil transference experiments (STEs) were undertaken to determine whether patterns identified in laboratory experiments could also be recognised at a simulated crime scene in the field. A clothed 55 kg human rescue dummy dressed in a padded bra was either dragged or merely placed on a soil surface at sites with natural and anthropogenic soil types under both wet and dry soil conditions. Transfer patterns produced by dragging compared favourably with those of laboratory experiments. Twelve patterns were identified when a clothed human rescue dummy was dragged across the two soil types in the field. This expanded the original set of eight soil transfer patterns identified from dragging weighted fabric across soil samples in the laboratory.

Soil transferred by placing the human rescue dummy resulted in a set of six transfer patterns that were different to those produced by dragging. By comparing trace soil patterns transferred to bras using each transfer method, it was revealed that certain transfer patterns on bras could indicate how the fabric had made contact with a soil surface. A photographic method was developed for crime scene examiners to capture this often subtle soil evidence before a body is transported or the clothing removed.

This improved understanding of the dynamics of soil transference to bras and related clothing fabric may assist forensic investigators reconstruct the circumstances of a variety of forensic events.

1. Introduction

Forensic soil examination has a wide range of advanced analytical methods available to compare soil with likely localities of origin [1–10]. These methods are generally defined as biological, chemical or physical. However, the way in which soil transferred by actions such as dragging has received little attention, apart from the early work of Locard in 1930 [11]. All other laboratory-based investigations have focused on the transfer of human-made manufactured materials such as textile fibres, glass, fluorescent powder, lighter flint particles and metal particles (glitter) [12–21].

This gap in forensic soil knowledge was an important issue in the interpretation of soil evidence in an Australian murder case [22,23]. A deceased female was found buried in park land. There was no evidence of violence at the burial site and it was deduced that the initial attack had occurred at a second location.

Traces of brick dust and soil on the victim compared closely with a brick driveway and soil from the victim's front yard indicating that this was the location of the attack. A trace amount of red brick dust, combined with natural soil objects, were lodged against the buckles and fasteners of the victim's bra. Similar trace soil evidence was embedded in scratches in her boots. Hard quartz particles had acted like 'glacial till'; gouging out brick dust from the red brick pavers [22]. A series of parallel scratches could be clearly seen with the unaided eye across metal buckles on one bra shoulder-strap [24]. The combination of soil, brick particles and scratches suggested that the victim had been dragged across the brick paving dusted with soil.

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Evidence relating to soil origin was accepted by the Judge that the initial attack on the victim occurred in the front yard of her home. However, the Judge disallowed interpretation of trace soil marks on clothing being used as an indication of the circumstances of the attack. He suggested that soil evidence on her clothes may have been the result of normal daily activities; or possibly carried by the wind into her clothes whilst they were drying on a clothes line. The Defendant was acquitted and Corryn Rayney's murder remains unsolved.

The circumstances in this case highlighted the lack of published research that would allow interpretation of trace soil patterns on clothed victims. Murray et al. [25] conducted a series of systematic laboratory-based experiments where weighted bras were dragged across various soil types. Analysis of the physical elements of transferred soil particles (colour, size, mineralogy) during these experiments showed that there was a range of indicators for dragging.

Image processing software was used to provide an objective assessment of the soil distribution on the fabric, referred to in this paper as 'trace soil patterns'; and Munsell colour classification of the soil that had been deposited. The software was also able to construct rose diagrams from the image data, which provided evidence of the direction from where the fabric was dragged. Relationships between the observed pattern and the soil type and particle size, clay mineralogy and soil moisture content were demonstrated. Using this methodology to systematically record and analyse the physical elements of trace soil patterns, before soil is removed for forensic analyses, may indicate whether a victim was dragged or placed upon a soil surface.

The objective of this paper is to report on the extension of the previous laboratory-based work to field-based experiments using a clothed human rescue dummy to simulate a victim. Methods of soil transfer were extended to include two distinct methods of soil transfer to fabric; dragging across both dry and wet anthroposol and natural soil surfaces and placement of the human rescue dummy upon the same soil surfaces. The effectiveness of the image processing technology to objectively interpret the transfer patterns was also investigated.

2. Material and methods

2.1. Experimental design: 'placing' and 'dragging' as methods of soil transfer onto bras

The objective of these experiments was to extend the soil transfer method simulated in previous laboratory experiments [25]; whilst confirming that trace soil patterns documented in the laboratory could also be identified in the field. To minimise external factors that might influence results or effect the reproducibility of these experiments, similar controls on soil transfer method had to be placed on 'dragging' soil transfer experiments (STEs) to mimic the soil transfer method previously tested in the laboratory.

Soil transfer methods were limited to testing either the 'dragging' or 'placing' of a semi-clad female body on different natural and HAHT soil surfaces because these were the most contentious issues involving forensic soil evidence during the Rayney murder trial. The lack of published literature testing even these most simple of soil transfer methods provided the incentive to field-test these two methods first. Resulting soil transfer patterns contained herein cannot be used to definitively prove a combination of these soil transfer methods or other situations not yet tested.

These experiments were designed to be the first step in providing forensic investigators with a methodology and classification system capable of interpreting the transfer method of trace soil evidence on clothing at crime scenes. To create a pristine record of trace soil patterns on clothing, photographs were taken immediately after the simulated victim's body was moved and before any clothing was removed.

This series of soil placing and dragging experiments dressed a human rescue dummy in a bra to:

Fig. 1. Photograph of the clothed 55 kg human rescue dummy wearing: (i) waterproof overalls, (ii) plastic clip-lock bags over its hands and head and (iii) a clean bra complete with "breast implants". The rescue dummy in the photograph is seen placed on a dry soil on the rose garden path during a 2 min "placement" soil transference experiment.

Table 1
Soil Transference Experiments (STEs) test two soil transfer methods (dragging and placing) using wet and dry soil.

STE	Transfer method	Soil moisture content
1	Dragging	Dry soil
2	Dragging	Wet soil (sprayed with water)
3	Placing	Dry soil
4	Placing	Wet soil (sprayed with water)

(i) test 48 bras for the persistence, size and quantity of soil transferred,
(ii) conduct 48 soil transference experiments (STEs) on bras,
(iii) use detailed image processing analyses of digital photographs to provide numerical data on different trace soil patterns on fabric by transfer method and soil location,
(iv) compare soil transfer patterns on bras resulting from the transfer methods of dragging and placing a clothed human rescue dummy on a soil surface.

A clothed human rescue dummy was used in the field at the Royal Tasmanian Botanical Gardens (RTBG) in Hobart Tasmania [25], to identify soil transference patterns when a clothed human body is placed or dragged across a soil surface. The human rescue-dummy was dressed in a padded bra. White wired sports bras (size DD bra-cup) of nylon-elastane clothing fabric were padded using 'implants' of rice-filled socks. Plastic bags protected the socks from soil contamination, enabling easy cleaning between STEs. Once fully attired, the modified LifeTec rescue training dummy weighed 55 kg in total.

Dry surface soil in the field naturally contained higher moisture levels than artificially dried soils used in previous laboratory experiments [25]. To artificially simulate rain or poorly-drained to water-logged conditions for wet soil STEs, mains water was sprayed with a hose attachment until soil changed colour evenly and water beaded. Because of this level of water saturation, we refer to this soil condition as "wet soil" rather than "moist soil" in this paper. It was noted during experiments that due to the depth of free-draining soil at the natural soil site, wet surface soil did not retain its higher moisture content for as long as did the poorly-drained HAHT path site.

One STE was conducted on each bra; with 24 bras used in dragging experiments and 24 bras used in placing experiments. To complete one 'placing' STE, the rescue-dummy wearing a clean bra was placed first on its chest and then on its back for two minutes; on either wet or dry soil at one location (Fig. 1 and Table 1). Digital photographs recorded soil transfer patterns first on the front side of the bra, and then after completing the STE on its back. To complete one 'dragging' STE, the rescue-dummy was dragged by its legs for three metres in a straight line, first on its chest and then on its back; across either wet or dry soil at one location (Fig. 2). Digital photographs were taken of the soiled bra still worn by the rescue-dummy immediately after every STE.

For the purpose of these experiments, a low-to-negligible persistence level was defined to be when a soil object rests loosely on the fabric surface and is easily transported across the fabric surface when the body is moved or clothing removed. A moderate-to-high level of persistence was defined to be when a soil object has either become immersed or amalgamated into the fibre strands, become interwoven with the weave of the fabric (such as a grass-seed) or firmly pushed under the bra itself (such as leaves or a twig).

Further data and information can be accessed in the Supplementary data about: (i) the properties of the sports bra used in all the field experiments and (ii) the experimental design of the field experiments conducted using the life-like rescue dummy.

2.2. Soil sites in the field

The two sites chosen in the Royal Tasmanian Botanical Gardens (RTBG) are shown in Fig. 3 and had previously provided three of seven soil samples that were used in laboratory experiments [25]. Morphological descriptions and classifications of the soil types at: (i) site 1, the anthropogenic soil type (Spolic Anthroposol [26], technosol, anthrosol or human-altered and human-transported material (HAHT)) and (ii) site 2 the natural soil type (Humose, Mesotrophic Brown Dermosol [26]), are summarised in Table 2. Colour photographs of sites 1 and 2 are presented in the Supplementary data. At site 1, the Anthroposol soil type comprises a hard gravel path, which was formed from transported road metal being placed over the original natural Dermosol soil type (light clay over heavy clay soil) (Fig. 3).

2.2.1. Colour measurement of soil transferred to fabrics

Munsell soil colour [29] is routinely used by forensic soil scientists to differentiate and characterise soil materials [30–32]. To make Munsell soil colour analysis accessible to police examiners untrained in forensic soil techniques, a method initially developed by Murray et al. [25], was tested at two sites shown in Fig. 3 to simulate crime scenes. Digital photographs taken immediately

Fig. 2. Photograph of the clothed human rescue dummy, dressed in a clean bra with implants being dragged three metres across a natural soil type at the Royal Tasmanian Botanical Gardens during a "dragging" soil transference experiment. Lifted by the legs, the dummy is dragged either on its back or front in two different soil transference experiments.

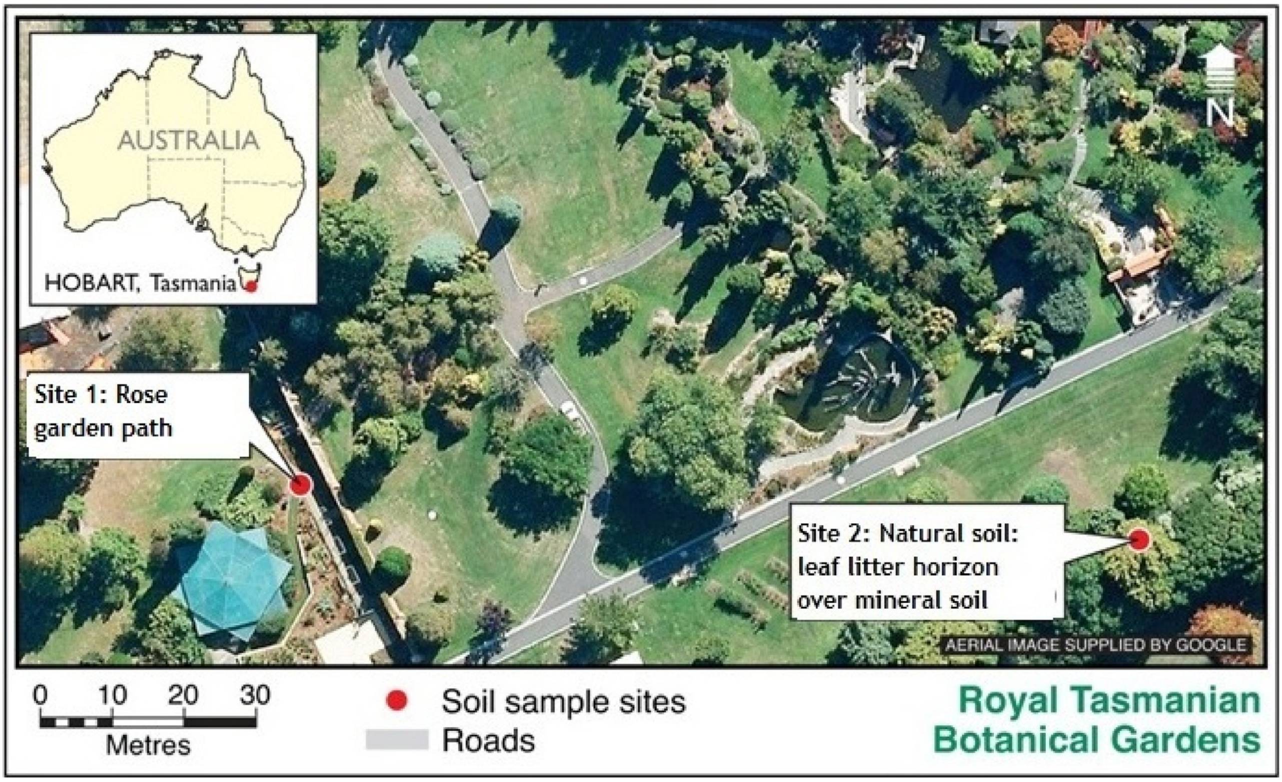

Fig. 3. Aerial photograph of the Royal Tasmanian Botanical Gardens showing the distribution of the two sites, which were used for the Soil Transference Experiments with the following soil types: (i) anthropogenic soil type along the rose garden path (Site 1) and (ii) natural soil type along the south-eastern fence (Site 2).

after each STE captured the colour of dry and wet trace soil transferred to fabric. Trimble eCognition Developer image processing software was programmed to reproduce specific ranges of Munsell colours (from a restricted range of 25 Munsell soil colours) for trace soil patterns from different STEs. During image preparation, the background surface areas were masked. Photographs were categorized by soil sample and further classified by wet or dry moisture content experiments. Image processing was used to identify dominant and subdominant peaks of different Munsell soil colours in both wet and dry trace soil on fabric using both transfer methods of placing and dragging (Figs. 7 and 8).

The quantity of different categories of soil particles (pale smears, brown smears and organic particles) were collated as a percentage of the total soiled fabric area in pixels and then compared with areas of clean fabric. The objects included solid clumps of soil, bark and plant fragments. There were also areas of stained fabric ("pale smears") probably due to the presence of finely dispersed clay (<2 μm) and iron oxide that were individually too small (<100 μm) to be included in the dataset for further analysis.

Directionality of soil clumps and stains, sorted by length/width (≥100 μm/2 pixel), revealed the dominant direction in degrees that soil was transferred to the fabric when either dragged or merely placed upon a soil surface. This numerical data was illustrated using rose diagrams created in GeoOrient [33]. Two STEs recorded in each category were combined into one rose diagram.

2.2.2. Recording of soil transfer patterns on clothing and image processing

To simulate the basic equipment carried by a crime scene photographer a 14.1 megapixel digital camera as described by Murray et al. [25] was used to record soil transfer patterns in the field. Further information can also be accessed in the Supplementary data.

3. Results

3.1. Trace soil patterns identified on fabrics using 'dragging' as the transfer method

The following 12 soil transfer patterns were identified and documented with dragging STEs conducted at both soil locations; but only the first five (5) patterns were identified with 100% consistency on all 24 bras (Please refer to online Supplementary data) (Figs. 4 and 5, and Table 3). Nine trace soil patterns were originally documented in laboratory experiments by Murray et al. [25]. Their reoccurrence in the field may indicate that this combination of trace soil patterns can reliably infer dragging as the method of soil transferred onto a clothed body. Three trace soil patterns, namely damage to fabric, soiled water stains and speckling of soil on fabric, are new patterns never before documented (Table 3). Additionally, the pattern of elongated (organic) soil particles aligned with the direction of dragging movement that was originally identified as an inconsistent and superficial surface-level pattern during previous laboratory experiments, was extended to incorporate elongated soil particles (twigs, leaves, grass seeds), being pushed under or into fabric during dragging experiments in the field (Fig. 4(C)).

Soil 'trails' (soil transfer pattern 1) was replicated with 100% consistency across all 12 dragging STEs conducted at both soil locations, regardless of whether soil was wet or dry. However, this pattern was absent in all placing STEs (Table 4).

Sporadic soil build-up on bra-strap edges (pattern 2) occurred with 100% consistency in all dragging STEs; whereas a minimal build-up was identified in a third of placing STEs.

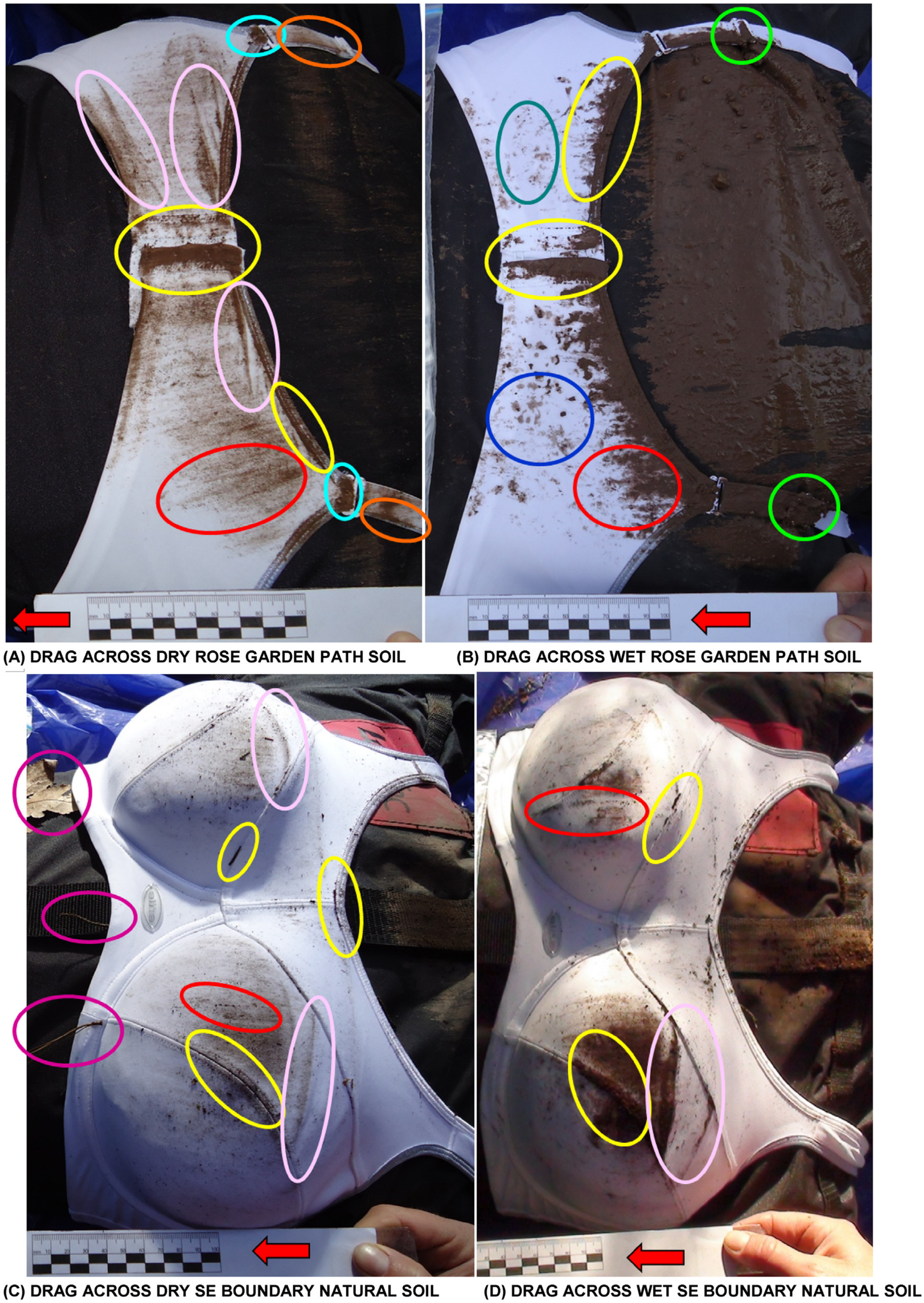

Fig. 4. Trace soil patterns produced when a clothed human rescue was placed on wet or dry soil and dragged in a straight line for three metres. Twelve trace soil patterns were identified by an initial visual analysis alone. (Notice changing lighting conditions and shadows on fabric required the white scale bar to be used as a colour standard to assist image processing). (Direction of movement = right to left).

Soil accumulated on raised surfaces (pattern 3) in 100% of all dragging STEs and in approximately half of all placing STEs at both locations, but to a relatively lower extent.

Soil on metal bra buckles occurred with 100% consistency in all dragging STEs. Half the placing STEs at the natural soil site showed

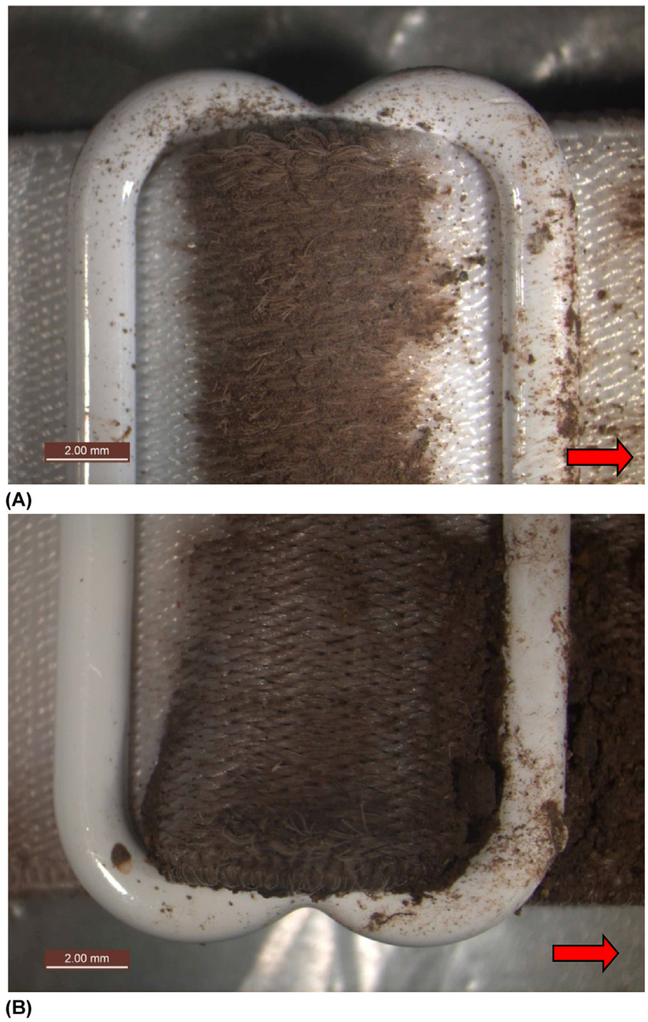

Fig. 5. Close-up photomicrograph of the fabric crossing over the bra buckle following the human rescue-dummy dragging over: (A) the dry anthropogenic soil type on the rose garden path showing the fabric crossing over buckle, which is frayed and distorted from its edge down the entire width of the strap and (B) the wet anthropogenic soil type on the rose garden path showing the fabric crossing over buckle, which is frayed on its edge. (Direction of movement = left to right).

a comparatively small quantity of soil accumulation on bra buckles and only one STE at the Rose Garden Path recorded this pattern.

Muddy clumps on wet shiny buckles (pattern 5) occurred with 100% consistency in both dragging and placing STEs at both soil sites when using wet soil. This pattern was also replicated in the three dragging STEs conducted using dry soil (not sprayed with additional water) at the Rose garden path site. This is likely due to the naturally high moisture content of soil at this poorly-drained site.

Fine soil particles were evenly dusted on bra-buckles (pattern 6) in all three dragging and placing STEs using dry natural soil. However, when the rescue dummy was dragged over dry soil with naturally high moisture content at the Rose Garden path, transferred soil particles formed clumps as described above.

Soil accumulated on fluffy raised seams (pattern 7) in 11 of 12 dragging STEs at both sites. During placing experiments, this pattern was only replicated in half the STEs using natural soil and only 1 of 6 at the Rose Garden path.

Fold and crease marks (pattern 8) occurred in all six dragging STEs using wet and dry soil at the Rose Garden path and in two-thirds of STEs at the natural soil site. Only one faint crease mark was identified in all placing experiments.

Damaged or frayed fabric (pattern 9) occurred with 100% consistency during the six dragging STEs on wet and dry soil at the Rose Garden path; likely due to its hard, compacted and gravelly surface (Fig. 5). No damage was identified from dragging STEs at the natural soil site or in any of the placing experiments.

Soiled water stains (pattern 10) occurred with 100% consistency in dragging and placing experiments using wet soil at the Rose Garden path but results were less consistent using wet soil at the natural soil site.

Elongated particles and larger soil objects were aligned and/or embedded in bra fabric (pattern 11) in 100% of dragging STEs using dry soil at the natural soil site and two-thirds of STEs at the Rose Garden path (Fig. 4(C)). This pattern did not occur when soil was wet, except for one STE using natural soil; which had a surface layer of undecomposed organic plant material of twigs, leaves and pine needles.

Speckling of soil on fabric (pattern 12) occurred in 3 of 6 dragging STEs at the Rose garden path and 1 of 6 STEs at the natural soil site. However, this pattern occurred with 100% consistency in all 12 placing experiments.

3.2. Trace soil patterns on fabric using the transfer method of 'placing'

Nine (9) transfer patterns were produced by placing the clothed human rescue-dummy for two minutes on wet or dry soil (Table 4). Only the first two (2) patterns were consistently produced in all 'placing' STEs at both sites on all 24 bras.

During 'placing' STEs, care was taken to minimise any movement of the fabric across the soil surface. Therefore, no soil trails were seen on bra-fabric, no elongated soil fragments were aligned or embedded; and bra-fabric remained undamaged. This was done to ensure to keep results consistent and as reproducible as possible for future forensic teams. However, at real crime scenes, it would be realistic to expect more complex and potentially confusing trace soil patterns; resulting from a combination of as yet untested new transfer methods.

3.3. Mineralogy and organic carbon

The mineralogical and geological composition of the Spolic Anthropogenic soil at site 1 along the Rose Garden Path comprises: (i) 40% weight of quartz, with 20% of both plagioclase and smectite clay [25] and (ii) 90% sandstone and mafic igneous gravel but with negligible organic matter. In contrast, the natural loamy soil at site 2 comprises approximately 20%, clay quartz and smectite with high organic content (38% weight organic carbon) [25]. Further information can also be accessed in the Supplementary data.

Wet soil STEs at both sites caused higher amounts of soil material to be transferred to the bra fabric after the rescue dummy was dragged across it than when soil was dry. At site 1 the high gravel content and hard surface of the anthropogenic soil type of the rose garden path caused damage and fraying of bra fabric crossing the metal buckles (Fig. 5(B)). At site 2, this transfer pattern and fabric damage was not observed for the natural soil type because of the very high organic matter content (>95%), which produced a soft friable soil surface and distinctive dark soil colour to the white bra fabric.

3.4. Munsell soil colour ranges of trace soil objects transferred to fabric in pixels

Murray et al. [25] provided detailed comparisons of initial Munsell soil colours chosen by an initial visual analysis and Munsell soil colour dominant and subdominant peaks identified by Trimble eCognition Developer image processing software. To improve the accuracy of image processing analysis, individual soil

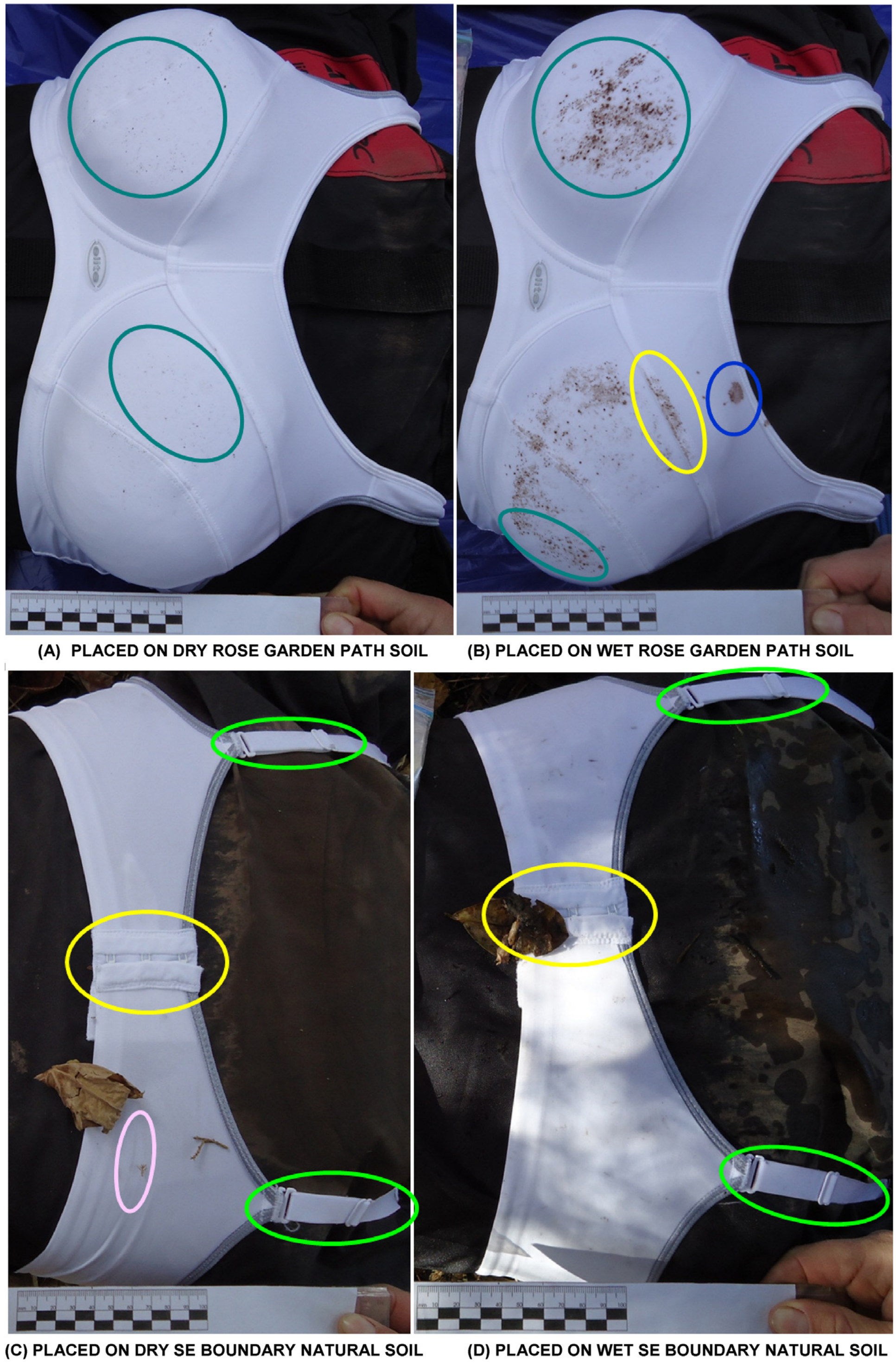

Fig. 6. Trace soil patterns using transfer method of placing the clothed human rescue-dummy on dry or wet soil types at two sites in RTBG. Nine trace soil patterns were identified by an initial visual analysis alone.

grains and aggregates from 2 pixels/≥100 microns diameter were mapped across the fabric surface. Smaller soil objects were excluded from analysis because the software was not programmed to reliably classify them. Similar dominant and subdominant Munsell soil colour peaks were recorded throughout the six trace soil patterns that originated from one of the two soil locations. An initial visual Munsell colour analysis of fine (<2 mm) fractions from the anthropogenic soil type of the rose garden path recorded 7.5YR 5/2 when dry and darker 7.5YR 3/2 when wet [25] (Table 2).

Digital photographs of dry trace soil ‘dragged’ onto fabric was analysed using image processing software with dominant colour peaks at 10YR 7/2 and 2.5YR 6/1; with minor peaks of 7.5YR 2.5/2 at 10YR 6/3. When wet, dominant colours of 10YR 7/2 and 6/3 were identified, with minor peaks occurring at 2.5YR 6/1, 7.5YR 2.5/2 and 10YR 5/3 (Fig. 7).

Dry ‘placing’ STEs displayed the same dominant colour as initially recorded by an initial visual analysis of 7.5YR 5/2; with minor peaks occurring at 2.5YR 6/1, 7.5YR 5/2, clustering at 10YR 4/

Table 2
Soil type, soil Munsell colour, brief soil description and soil classification based on the Australian Soil Classification [26] and World Reference Base for Soil resources [27] of two sites in the Royal Tasmanian Botanical Gardens.

Locality (depth cm)	Centre for Aust. Forensic Soil Science (CAFSS) code	Munsell[a] soil colour <2 mm fraction (wet) (dry)	Soil type[b]	Brief description	The Australian soil classification	The world reference base for soil resources
Site 1: rose garden path (0–10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	Anthropogenic, gravelly sandy loam soil	Gravel (90%; arkosic sandstone and andesitic-to-weathered mafic igneous rock) loamy sand, water repellent, 0.7% Carbon (C).	Spolic anthroposol; very gravelly, sandy, very shallow	[c]Spolic technosol (Densic)
Site 2: south-east boundary (5–0 cm)	110.9.1	Leaves not analysed for Munsell soil colour by naked eye	Natural, organic-rich soil	Undecomposed Leaves (60%) and decomposed (40%)	Humose, Mesotrophic, Brown Dermosol; non-gravelly, loamy, deep	[d]Eutric Cambisol (Humic)
(0–10 cm)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	Natural, loamy soil	Gravel (2%), loamy sand, water repellent, 23% C.		

[a] Munsell Soil Colour [36]: measured using the fine earth fraction (<2 mm).
[b] A special-purpose technical soil classification system [28].
[c] Classification of Technosols [27].
[d] Classification of natural soils with substantial soil formation, including Cambisols [27] and Dermosols [26].

2, 5/3, 6/3 and 7/2. When wet, the same colour peaks were displayed.

Initial visual Munsell colour analysis of fine fractions from the natural soil type recorded 7.5YR 2.5/2 when dry and darker 10YR 2/2 when wet [25] (Table 2). The natural soil surface horizon composed of dry leaves was omitted from analysis by an initial visual analysis due to lack of mineral soil content.

Dry trace soil ‘dragged’ onto fabric and analysed by image processing software displayed a dominant Munsell colour peak at 7.5YR 2.5/2, with minor peaks at 2.5YR 6/1 and 10YR 7/2 (Fig. 8). When wet, dominant colours clustered at 7.5YR 2.5/2, 3/2, 3/4 and 10YR 7/2. Minor peaks occurred at 2.5YR 6/1 and 10YR 6/3.

After dry ‘placing’ STEs, image processing recorded dominant colour peaks at 10YR 6/3 and 7/2; and minor peaks at 2.5YR 6/1, 7.5YR 2.5/2 and 10YR 5/3. When wet, dominant peaks at 7.5YR 2.5/2 and 10YR 6/3 and 7/2 were identified; with a minor peak at 2.5YR 6/1.

3.5. Directionality

It has been shown by Murray et al. [25] that Trimble eCognition Developer imaging processing software can be used to construct Rose diagrams to reveal directionality in soil transfer patterns. Directionality was identified by image processing as being a microscopic alignment of individual soil objects on or in the clothing fabric and soil ‘trails’ or stains. This same technique was applied in these field experiments. Using image processing directional or orientation from digital photographs of bra-cups (not bra-straps), these rose diagrams [33] mapped directionality of thousands of wet or dry soil particles ≥2 pixel diameter on fabric. As shown in Fig. 9, ‘dragging’ STEs displayed strong uni-modal to moderate bi-modal directionality. Black directional lines had reached the outside edges of the rose diagram; aligned with prime direction of movement recorded by source photographs of soil ‘trails’ on fabric (right to left). Dry soil objects showed a tendency to gather against bra-cups’ perpendicular middle seam. Each rose diagram combined directional data from close-up photos of either left or right bra cups. During the dry soil STEs conducted at this site, photos of both left and right bra cups was analysed. In accordance with previous laboratory experiments [25], dry soil from the rose garden path tended to persist on the perpendicular-to-diagonal middle seam of each bra cup. Because directional data from both left and right bra cups was combined (with middle seams at opposing angles), a cross-like diagonal pattern was formed. When wet soil from this site was photographed, bra cups from one side were chosen, showing a build-up of soil on perpendicular seams that were all at the same angle. Further information on the image processing methods and data can also be accessed in the Supplementary data (Section 4).

During ‘placing’ STEs, minimal trace soil was transferred. A more random and scattered directionality resulted compared to ‘dragging’ STEs. In placing STEs, there was no overriding mono-directional alignment of soil particles, as seen to greatest effect in dragging STEs over wet soil. There was no definite bi-directional ‘cross’ shape caused by loose dry soil particles gathering against a perpendicular clothing seam during dry soil dragging STEs. In placing STEs, the pattern became more like an asterisk, with soil particles scattered randomly in all directions in the very centre of the rose diagram.

3.6. Quantity of trace soil objects transferred to fabric and analysed by soil type

Trimble eCognition Developer image processing analysis of digital photographs taken of trace soil transferred to clothing fabric (bra) provided objective numerical data regarding the quantity of soil objects transferred to fabric [25]. After the initial time spent programming the software to identify soil objects on clothing fabric, the actual processing of each digital photograph only took 1–2 min. This process could be sped up if the software was programmed to run analyses automatically instead of by manual input. Quantitative graphical presentation of trace soil patterns integrated the properties of the soil types tested such as mineralogy, chemistry, texture and gravel content, moisture content, directionality and quantity of soil transferred. This standardised objectivity was not possible using an initial visual analysis of a clothing surface. Image processing numerical data has been summarised in Table 5 and Fig. 10.

In accordance with previous laboratory methods [25], soils were grouped according to location and soil moisture content and the numerical data averaged.

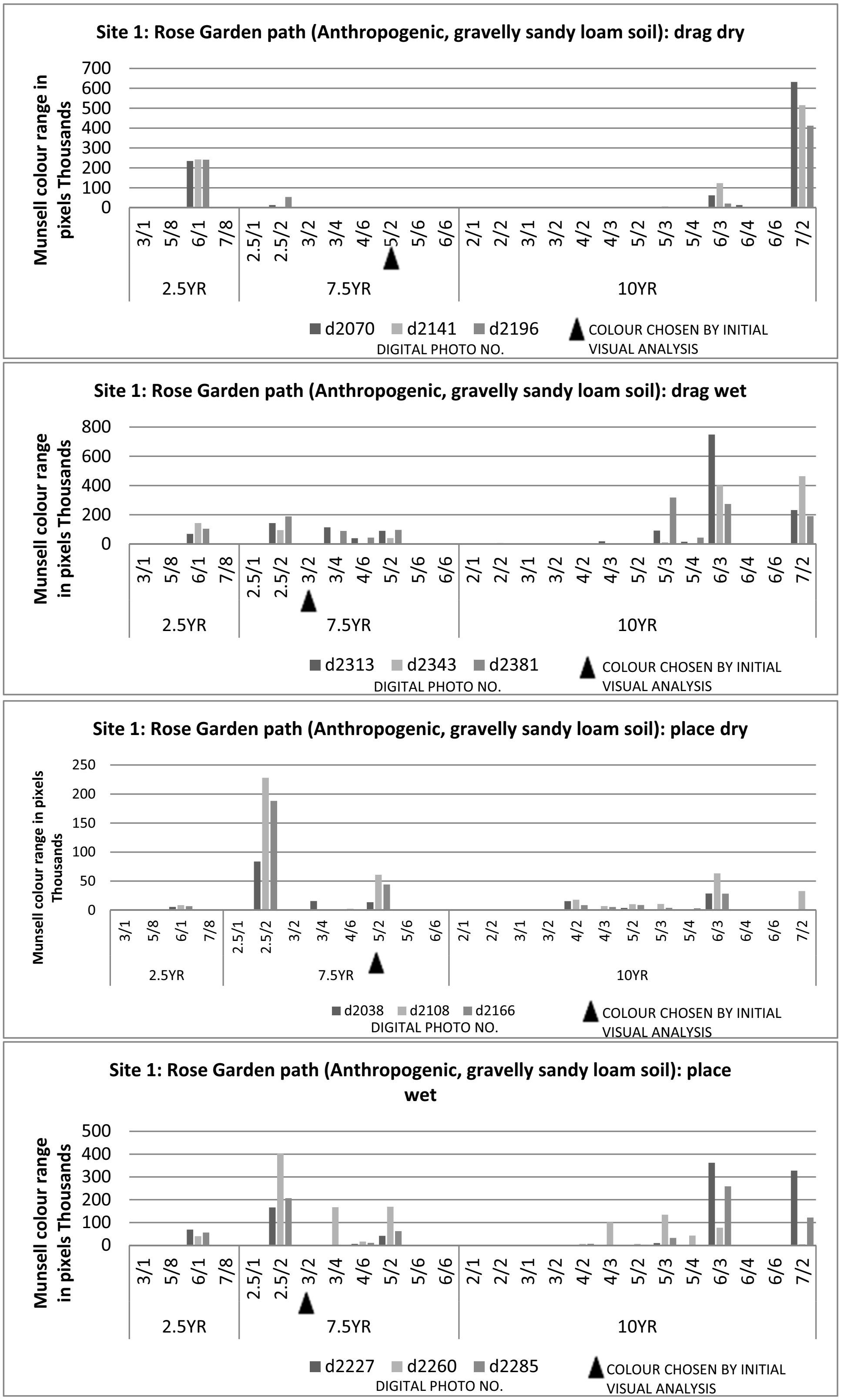

Fig. 7. Munsell soil colour ranges were recognised by image processing software using digital photographs of the anthropogenic soil type of the rose garden path. Dry and wet soil was transferred onto fabric using transfer methods of dragging and placing. Results from three STEs were combined in each graph.

Soil objects covering >0.5 million pixels were categorised as a low quantity of trace soil particles transferred to fabric.

Soil objects that covered 0.5 million to >1 million pixels were categorised as a moderate quantity of trace soil transferred.

Soil objects that covered 1 million pixels and above were categorised as a high quantity of trace soil transferred.

Image processing provided numerical data to measure the quantity of trace soil objects (both aggregates and individual soil

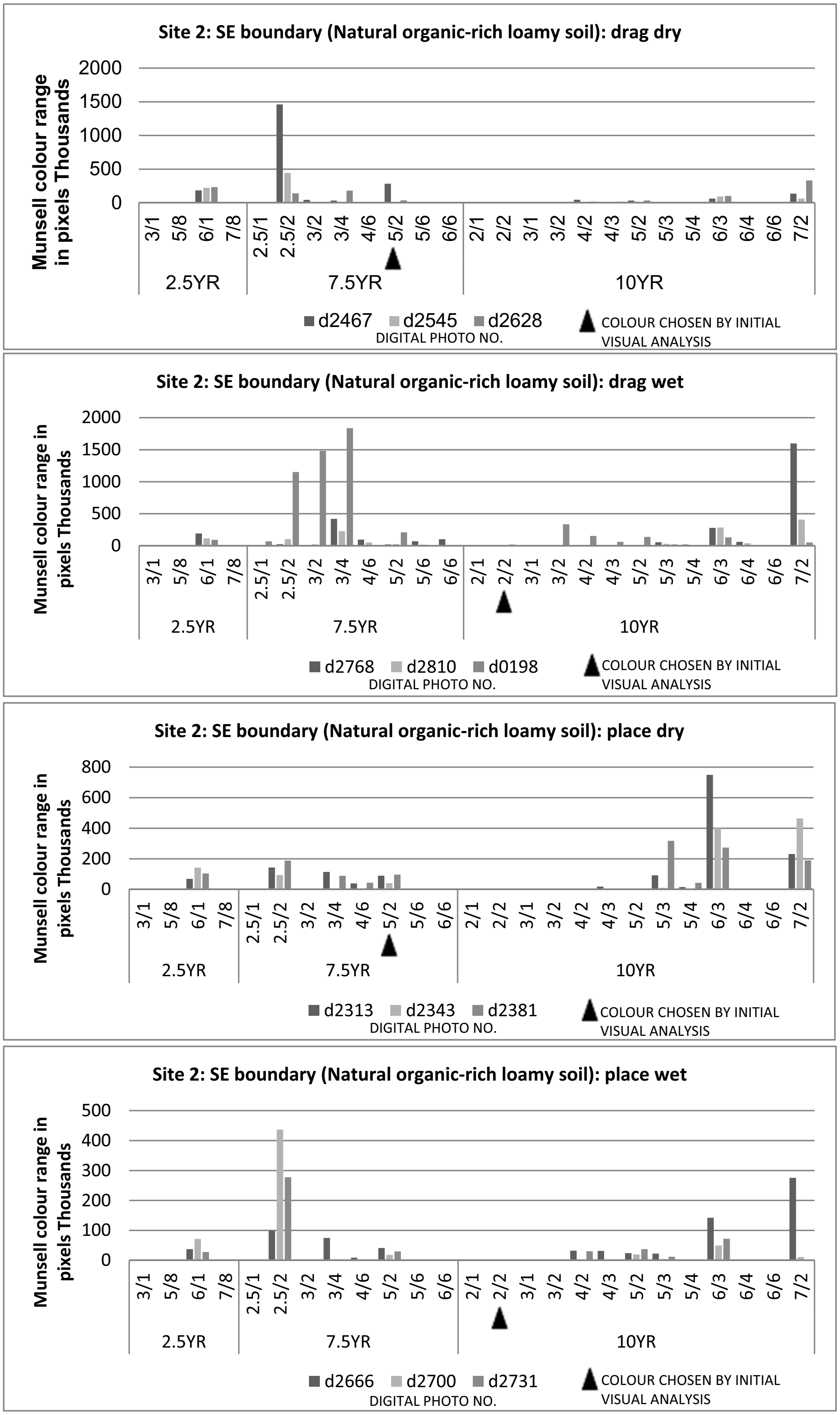

Fig. 8. Munsell soil colour ranges were recognised by image processing software using natural soil type on the SE boundary of the Royal Tasmanian Botanical Gardens transferred onto clothing fabric when dry or wet using transfer methods of dragging and placing. Results from three STEs are combined in each graph.

objects) transferred to fabric. Individual soil objects were those with a distinct outline and aggregates incorporated larger masses of soil objects.

In summary, both soil types produced only a low amount of trace soil transferred to fabric when the clothed human rescue dummy was merely placed on either a dry or wet soil surface.

Table 3
Trace soil patterns identified on fabric using 'dragging' as the transfer method.

	Soil transfer pattern	Symbol used	Figure	Location on fabric	Contributing soil characteristic
1	Soil 'trails'	red circle	Fig. 4	parallel to direction of movement	Greater quantity of wet soil objects transferred than dry
2	Sporadic soil build-up on edges	orange circle	Fig. 4(A)	shoulder-strap fabric edges	no consistent trends
3	Soil accumulated on raised surfaces	yellow circle	Fig. 4	raised middle seams and back fasteners perpedicular to direction of movement	no consistent trends
4	Soil on metal buckles	green circle	Fig. 4(B), Fig. 5	bra-strap buckles and fabric directly in front	no consistent trends
5	Muddy clumps on wet shiny buckles	–	Fig. 5(B)	bra-strap buckles	wet or poorly-drained soil
6	Evenly 'dusted' buckles	–	Fig. 5(A)	bra-strap buckles	very dry soil
7	Soil accumulated on fluffy raised seams	aqua circle	Fig. 4(A)	ends of bra-straps	no consistent trends
8	Fold and crease marks	pink circle	Fig. 4(A), Fig. 4(C), Fig. 4(D)	approx. parallel to direction of movement	no consistent trends
9	Damaged or frayed fabric	–	Fig. 5	fabric crossing metal bra-strap buckles	hard gravel-textured soil
10	Soiled water stains	dark blue circle	Fig. 4(B)	sporadically where fabric had made contact with soil surface	wet soil
11	Elongated particles aligned and/or embedded	purple circle	Fig. 5(C)	embedded in or under fabric parallel to direction of mov't	no consistent trends
12	Speckling of soil on fabric	turquoise circle	Fig. 4(B)	sporadically where fabric had made contact with soil surface	no consistent trends

When dragged across a dry or wet soil surface, the amount of trace soil transferred to clothing increased to a moderate amount for the natural soil type on the SE boundary (Fig. 3). The Spolic Anthropogenic soil type with high gravel content and hard surface on the rose garden path produced a high to very high quantity of trace soil transferred during dragging STEs. Regardless of whether the placing or dragging method was used, wet soils produced a larger amount of trace soil material transferred onto fabric; with a higher percentage of aggregates due to a tendency for soil types tested to clump together with increased moisture content [34]. The greatest abundance of soil transferred, by far, was achieved by the transfer method of dragging.

4. Discussion

Since initial research conducted using Munsell soil colour and image processing to analyse trace soil patterns on clothing was published [25], interest in these new uses for existing Munsell colour and software programming processes has been shown by soil scientists and computer software developers alike [36,37]. The results of these field experiments provided practical confirmation that soil transfer patterns can be identified and categorised by two main methods of transfer (dragging or placing); including whether soil was dry or wet when transferred to fabric. The trace soil patterns documented in this paper can only indicate when a single transfer method, either dragging or placing, has occurred to a human body wearing tightly fitting clothes. Further STEs are required to understand soil transfer dynamics and patterns in alternative forensic scenarios; such as when a body is wearing very loose-fitting clothing and is placed on a soil surface, or identify soil patterns produced when a conscious victim is struggling violently. When trace soil pattern analysis on clothing becomes prioritised as an important source of forensic soil evidence at a crime scene, it is anticipated that forensic examiners will be required to interpret much more complex trace soil patterns than depicted in this study. This will necessitate additional testing being undertaken to explore the effects of humidity, quantity of movements or actions and extremes of weather conditions. When multiple soil transfer methods have occurred, forensic examiners may be more reliant on image processing software to decipher directionality of soil objects

Table 4
Trace soil patterns on fabric using the transfer method of 'placing'.

	Soil transfer pattern	Symbol used	Figure	Location on fabric	Contributing soil characteristic
1	Speckling of soil on fabric	turquoise circle	Fig. 6(A), Fig. 6(B)	sporadically where fabric had made contact with soil surface	wet soil objects were often emedded or semi-dissolved into fabric
2	Buckles shiny clean	green circle	Fig. 6(D)	bra-strap buckles	wet soil
3	Soiled water stains	dark blue circle	Fig. 6(B)	sporadically where fabric had made contact with soil surface	very wet soil
4	Minute amounts of soil on raised surfaces	yellow circle	Fig. 6(B), Fig. 6(D)		Greater quantity of wet soil objects transferred than dry
5	Soil accumulated on fluffy raised seams	green circle	Fig. 6(C), Fig. 6(D)	ends of bra-straps	no consistent trends
6	Unevenly 'dusted' buckles	green circle	Fig. 6(C), Fig. 6(D)	bra-strap buckles	very dry natural soil
7	Negligible soil on fabric crossing buckle	green circle	Fig. 6(C), Fig. 6(D)	bra-strap buckles	no consistent trends
8	Minimal to negligible soil accumulated on fabric edges	green circle	Fig. 6(C), Fig. 6(D)	bra-strap fabric edges	no consistent trends
9	Crease mark	pink circle	Fig. 6(C)	single faint crease where fabric made contact with soil surface	no consistent trends

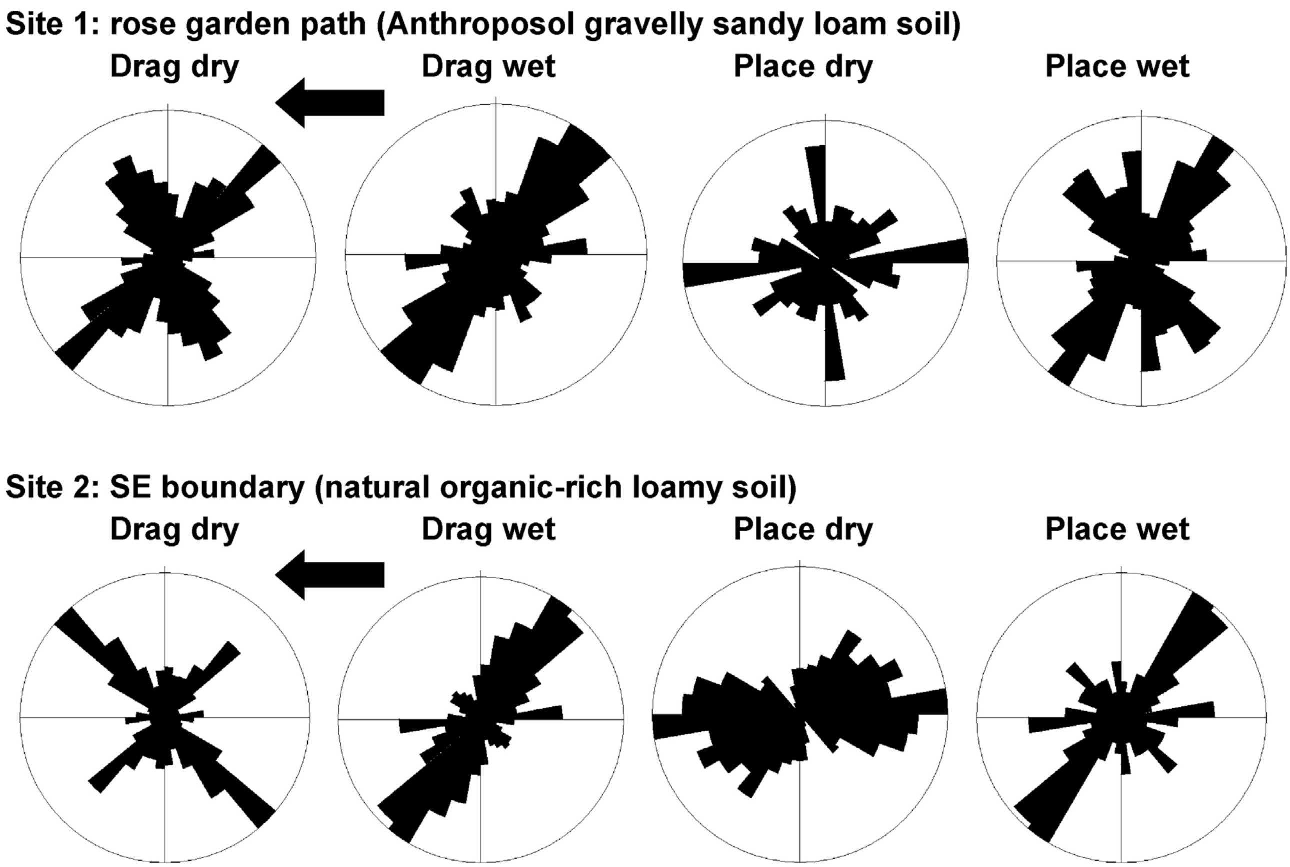

Fig. 9. Rose diagrams display directionality of wet and dry soil transferred by dragging or placing fabric on two different soil types. Strong uni-modal directionality resulted when clothing fabric was dragged in only one direction across the two soil types (right to left). Dry soil particles more than wet soil showed a tendency to gather against the middle seam. This created a more bi-modal directionality. 'Placing' STEs resulted in a more random and scattered lack of directionality.

on clothing fabric; another technique developed by Murray et al. [25].

Similar to the laboratory-based findings of Murray et al. [25], most soil objects transferred to clothing fabric were very fine silt-sized or clay-sized (<2 μm) fragments [13]. The largest soil object transferred was a 10 × 4 mm gravel particle. When removing the bra from the rescue-dummy, as expected larger (>0.5 cm) loose soil objects easily dislodged. Fine soil fractions that were transferred in soil trails had a tendency to remain half-embedded in fabric.

In order to maximise the reconstructive potential of trace soil evidence transferred to fabric, digital photographs focusing on all trace soil patterns on clothing will likely provide an optimal record of any adhered forensic evidence; before such patterns are destroyed or diminished by soil particles being lost or redistributed across the fabric during transport, removal of clothing from the victim or crime scene.

Trace soil patterns such as soil 'trails' and areas of soil accumulation on tightly-fitting clothes, when seen in relation to their position on the human body, can be used to discern whether the body was dragged by one or both hands or feet. However, if the body has been moved or clothing removed before the forensic examiner attends the crime scene, any such changes must be taken into consideration when interpreting the position of trace soil patterns on clothing.

Highly rigorous or destructive testing procedures, often undertaken in forensic laboratories, would destroy all but the most persistent trace soil patterns [24].

All soil textures (loamy-sand and undecomposed leaves) tested (Table 3) produced soil transfer patterns. When wet, clay-size (<2 μm) objects coated or impregnated fabric fibres; securing larger grains and stabilising soil aggregates [1,38]. This increased the quantity and persistence of the soil objects transferred.

Soil moisture greatly influenced the intensity of soil transfer patterns, soil quantity, particle size, persistence and mineralogy of particles transferred. 'Placing' STEs using metal bra-strap buckles were 'dusted' with fine soil using natural soil, as expected from previous laboratory research [25]. However, higher soil moisture content of the poorly-drained or wet anthropogenic soil type, produced clean buckles imitating a transfer pattern that only occurred in previous laboratory experiments when wet soil was tested [25]. Therefore, the natural water content of 'dry' and 'wet' soil at each crime scene will need to be taken into consideration before interpreting trace soil patterns to indicate weather conditions at the time of the attack. For example, wet soil transferred to clothing may indicate it was raining when the soil was transferred. Alternatively, it may indicate that soil originated from a poorly-drained site, ditch or riverbank.

Speckling of fabric, a transfer pattern characteristic of 'placing' STEs, occurred sporadically in some 'dragging' STEs; possibly due to the rescue-dummy being placed for 5 s on soil before and after dragging. It is important to consider the potential implications of these experiments for forensic investigations involving trace soil evidence on clothing fabric.

An excellent indicator that a clothed victim had been dragged was documented when organic soil objects (such as sticks and leaves) were pushed underneath clothing items or embedded in the fabric. The former was seen at Site 2 when after the clothed human rescue dummy was dragged for 3 m in a straight line, leaves, twigs and pine needles were pushed under the bra itself, aligned with the known direction of movement (Fig. 4).

Table 5
Summary of soil data gathered using an initial visual analysis, XRD and NDIR analysis and image processing analysis of three soil types and the trace soil transferred onto bra fabric. For convenience, moist soil is referred to as 'wet'.

Locality (depth cm)	Centre for Aust. Forensic Soil Science (CAFSS) code	Munsell[a] soil colour <2 mm fraction (wet) (dry)	DRAGGING STE Dominant trace soil[b] Munsell colour (wet) (dry)	PLACING STE Dominant trace soil Munsell colour (wet) (dry)	DRAGGING STE Average soil transferred (individual + aggregates) in pixels[c] (wet) (dry) High quantity Moderate Low	PLACING STE Average soil transferred (individual + aggregates) in pixels (wet) (dry) High quantity Moderate Low	Weight % clay content[d] (smectite)	% Organic content[e]	% Gravel content[f]
Site 1: rose garden path (0–10 cm)	110.5.1	**Dark brown**	**Pale brown**	**Pale red**	**4393337**	**361309**	19 ± 3	0.70	90
		7.5YR 3/2 Brown 7.5YR 5/2	**10YR 6/3** Light gray 10YR 7/2	**10YR 6/3** Very dark brown 7.5YR 2.5/2	1615060	2635			
Site 2: south-east boundary	110.9.1	**Leaves**	**Light gray**	**Very dark brown**	**907017**	**342560**	No XRD analysis	No NDIR analysis	Leaves
(5–0)		leaves	**10YR 7/2** Very dark brown 7.5YR 2.5/2	**7.5YR 2.5/2** Dark brown 7.5YR 3/4	534742	36034			
(0–10)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown **7.5YR 2.5/2**	**Both 9.1-2 horizons analysed together**	**Both 9.1-2 horizons analysed together**	**Both 9.1-2 horizons analysed together**	**Both 9.1-2 horizons analysed together**	20 ± 3	22.8	2

[a] Munsell Soil Colour [29]: measured on the fine (<2 mm) earth fraction.
[b] Munsell Soil Colour [29] measured using image processing software and combining three digital photographs of trace soil objects on clothing fabric.
[c] An average of the three STEs tested using dry or wet soil samples.
[d] 6 XRD analysis of % weight of clay (smectite) content from homogenous bulk soil samples.
[e] 6.1 NDIR analysis of the organic content from homogenous bulk soil samples.
[f] 6.2 Estimate by an initial visual analysis using method of McDonald and Isbell [35].

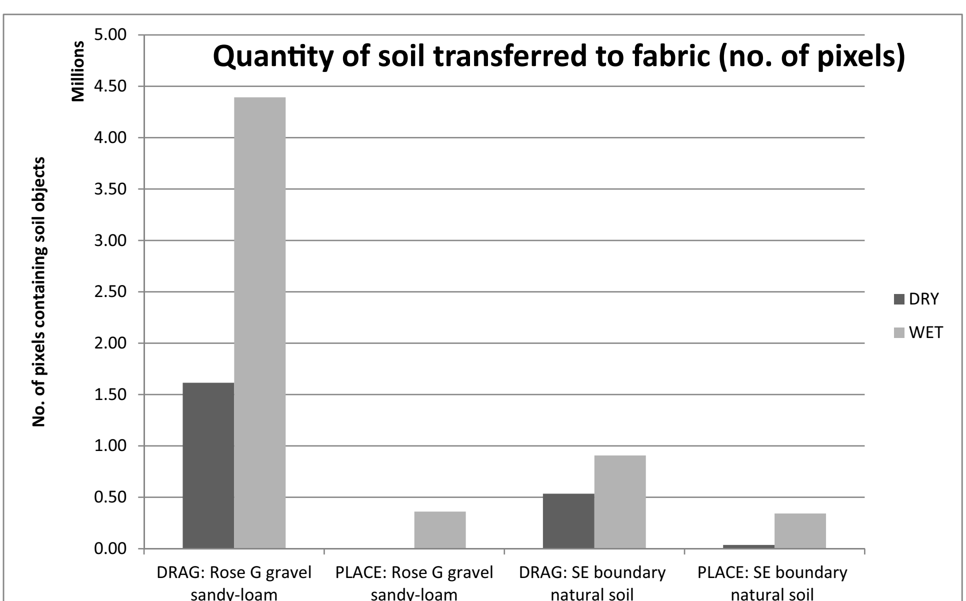

Fig. 10. Quantity of soil objects transferred to fabric was analysed using the number of pixels in simple digital photographs. Image processing numerical data was subdivided by location and wet or dry soil conditions [25].

4.1. Image processing analysis of trace soil transferred to fabric

Building on the research by Murray et al. [25], Trimble eCognition Developer image processing software continued to reproduce specific ranges of Munsell colours (from a restricted range of 25 Munsell soil colours) for trace soil patterns from different STEs. Image processing matched the same dominant and subdominant peaks of Munsell soil colours in both wet and dry trace soil on fabric using both transfer methods of placing and dragging (Figs. 7 and 8). Very similar dominant and subdominant colour peaks, specific to an individual soil type originating from a specific site, were chosen from a limited range of 25 Munsell soil colours. Image processing colour analysis was also sensitive enough to detect Munsell colour changes when trace soil transferred was wet or dry. Digital photographs taken immediately after each STE captured the colour of wet trace soil transferred to fabric.

Despite the valuable numerical data provided by image processing software, there were limitation in its capacity to differentiate certain sized or coloured objects. At its current level of programming, the software could not differentiate reddish-brown organic particles such as plant bark or dark leaf matter from reddish-brown mineral-based soil particles. The software could not reliably delineate the elongate outline of a 0.5 cm stalk of straw if encroached by mineral soil aggregates. Soil objects with an area less than 2 pixels were excluded from sorted results because the software could not reliably classify objects less than 100 by 50 microns. The software had some difficulty identifying the perimeter of areas of dark-coloured objects from adjoining shadows on the fabric. When analysing photographs taken in the field under the shade of surrounding vegetation, dark areas of shadow were incorrectly classified as dark coloured soil objects by the software. These shadow areas had to be cropped out before the remaining fabric area could be accurately classified. If the fabric colour had not been homogenous, this task would have been much more challenging.

Due to changing natural lighting conditions and the shadow of vegetation on clothing fabric in some of the digital photographs, initial Munsell colours chosen for soil types by initial visual analysis under optimum natural daylight conditions differed from those detected using image processing analysis. Despite the limitations of basic source photographs, the Munsell soil colour of fine dry trace soil transferred by both dragging and placing the clothed human rescue dummy on soil at both sites matched the Munsell colour chosen by initial visual analysis; albeit as one of the subdominant colours. Regardless of transfer method, the Munsell colour of wet trace soil from rose garden path also correlated closely with the Munsell colour initially chosen by initial visual analysis.

A relationship between soil type (Table 2), clay and soil moisture content was identified when graphical representations of image processing numerical data were created that measured the quantity of soil objects transferred to fabric. During dragging STEs, a far greater quantity of soil was transferred to fabric than by merely placing the rescue dummy on the soil surface.

During 'placement' STEs, both soil types produced a low quantity of soil objects transferred to fabric. An increase was seen in both soil types in the quantity of soil objects transferred when the soil was wet, but results remained in the low category of soil objects transferred. The anthropogenic, hard-packed, gravelly, sandy loam dry soil (Table 2) with low organic carbon content (rose garden path), transferred a low amount of very dark brown soil objects to fabric; increasing in quantity but remaining within a low category when wet (very dark brown) (Table 3).

The organic-rich natural soil type at site 2 (Table 2) with very high organic matter content (>95%) overlies a loamy soil material containing approximately 20% smectite. This surface soil with soft soil consistency because of the high amounts of organic matter, transferred a low quantity of pale brown soil objects to fabric when dry; increasing in quantity but remaining in the low category when wet (very dark brown) (Table 3).

In dragging STEs, the dry anthropogenic soil on the rose garden path transferred a high quantity of light gray soil objects to fabric; increasing by approximately 63% to a very high quantity of pale brown soil objects when wet.

The dry natural organic-rich soil transferred a moderate amount of very dark brown soil objects. When soil was wet, trace soil increased in quantity by 41%, but remained within the moderate category (very dark brown) (Table 3).

The marked differences in quantity of dry and wet soil objects transferred using placing or dragging transfer methods, regardless of soil composition, may begin to explain forensic soil evidence on the victim's clothing in the aforementioned murder case [22,23]. Negligible natural soil from parkland persisted on the victim's clothing when she was placed in a hole and buried for eight days. However, a relatively high quantity of Anthroposol trace soil persisted on her bra (in particular the bra shoulder-straps), deeply infiltrating the fibres [24]. This may imply a more forceful transfer method occurred during the initial attack, than merely placing the victim on soil.

4.2. Potential use of image processing analysis for soil evidence

These field experiments demonstrate the potential for using image processing software in analysis of crime scene photographs of soil patterns on clothing fabric. Trace soil on clothing can be analysed using a unique range of Munsell soil colours, soil object directionality and quantity of soil transferred; which is compared by soil type. XRD analysis is routinely used during major criminal investigations to analyse mineral composition of trace soil patterns on clothing fabric [1–4]. However, in those cases where soil evidence from different locations shared very similar mineralogy, image processing of crime scene photographs of soil evidence could be used to further differentiate trace soil evidence on clothing into subgroups of soil evidence; possibly originating from a similar source location.

In these field experiments, digital camera resolution was only 14.1 megapixels and only 25 of 450 standard Munsell soil colour chips were inputted for recognition by image processing software. Outdoor lighting conditions were variable, with digital photographs of soil transfer patterns at the natural soil type taken in dappled light due to overhanging vegetation. Trace soil photographed in deep shadow was omitted from analysis due to limitations in software programming.

Using a white scale bar as a simple colour standard, image processing analysed each photograph for Munsell soil colour via a basic PC computer back at the laboratory. Once the image processing software had been programmed to identify soil objects on clothing fabric, a comparison of the Munsell colour of soil objects on fabric using digital photographs took only minutes to produce quantifiable numerical data for simple Excel graphs. Using one specific scale bar as a colour standard could enable photographs taken under different lighting conditions at multiple locations to be compared. After initial programming, image processing software took only minutes to analyse each photograph. Using image processing as a tool of initial analysis may help focus resources on soil evidence that share a high degree of comparability.

Rose diagrams plotted directionality of trace soil objects transferred onto fabric that indicated a strong uni-modal to bi-modal directionality in 'dragging' STEs based on the laboratory results of Murray et al. [25]. Bi-modal directionality was largely due to soil objects being 'dammed up' against the middle seam during dragging experiments. This was particularly the case with dry loose soil objects. This contrasted markedly with minimal trace soil scattered randomly in 'placement' STEs. By combining image processing analysis with rose diagrams, directionality of soil objects transferred that were recognised using an initial visual analysis could also be objectively identified by image software. This technique could assist in the analysis of trace soil transferred onto clothing fabric; accompanying conventional forensic soil techniques such as light microscopy, Scanning Electron Microscopy and XRD [39,40]. The standardised objectivity provided by combining these techniques could better enable a court of law to understand and accept the circumstances by which fabric made contact with a soil surface.

At an authentic crime scene, it is realistic to expect some time to elapse before the victim is discovered. The impact of changing weather conditions, such as rain, sun and wind must be taken into account when interpreting trace soil evidence on a clothed body left outdoors for days, weeks or months. Trace soil patterns indicating the circumstances of an attack may be contaminated by scavenging animals potentially moving the body or tearing at clothes. If clothing to be analysed was blood-soaked, smeared or spattered with blood, image processing software would need to be programmed to differentiate the colour of fresh and dried blood from potential Munsell soil colours; or blood-soaked fabric areas would need to be masked off and omitted from analysis.

When interpreting trace soil evidence as part of a criminal investigation, the focus should be on identifying more persistent trace soil patterns that infer a specific method of soil transfer. Soil 'trails' on a clothed body are a strong indication that at some stage during or after an attack, the body not only made contact with a soil surface but was moved across it from A to B [11]. A dragging event only lasting three seconds showed a soil trail [25]. Regardless of the variety of transfer methods not yet tested, if soil trails are identified on a clothed body at a crime scene, dragging must be considered as one of the methods of soil transfer.

Soil transfer patterns caused by movement of weighted fabric across a soil surface, such as soil 'trails' and organic particles jammed under clothing or penetrating textile fibres, strongly indicate a body has been dragged across the soil surface. Damage to clothing fabric, impregnated with fine soil objects, or scratches on metal buckles, are extremely strong indicators that the victim had been dragged across a hard soil surface. The scenario of a body being dragged for longer than 3 metres across a softer loamy soil surface to test for fabric or buckle damage was not undertaken in these experiments. However, if the only trace soil pattern existing on clothing was a speckled pattern of trace soil objects, this could indicate that the victim was only ever placed on a soil surface when in a drugged, unconscious, physically immobilised or deceased state.

Rose diagrams could be used to illustrate image processing numerical data of the directionality of soil objects transferred. This could not only assist police investigators to understand the circumstances of an attack, but could potentially provide graphic, objective and easily understood documentation of this evidence in a court of law.

If image processing software was programmed to identify the full range of 450 Munsell soil colours, a more extensive Munsell soil colour range could potentially be identified for trace soil on clothing. Dominant and subdominant soil colour peaks of trace soil on clothing could quickly be compared using a computer with image processing software at the local police station, with known, questioned and alibi soil samples. This simple but powerful method could enable police to discover immediately whether criminal acts against the victim had occurred at more than one location. This may focus their investigation on a particular suspect or eliminate others from inquiry.

This paper provides practical evidence that trace soil patterns originally documented by Murray et al. [25] for laboratory experiments can be reproduced under realistic field conditions using a simulated human body. To strengthen police forensic investigators' interpretation of trace soil evidence on clothing in a court of law, it would be valuable to run several quick and simple STEs on soil in close proximity to the crime scene and other soils of interest to the investigation. Using the method of Murray et al. [25], fabric similar to the victim's clothes could be weighted to simulate a clothed human body (by attaching fabric to a flat dumbbell-weight with a dragging line) and placed or dragged across dry and wet soil surfaces. Each STE would take only seconds to run. If trace soil patterns and Munsell soil colours similar to those appearing on the victim's clothes were reproduced using soil in close proximity to the crime scene, these simple forensic soil tests may strengthen police interpretation of circumstances befalling a victim during or after an attack. In criminal cases where there is no DNA or fingerprint evidence, or reliable witness testimony, a soil location's highly individualised mineralogy has the potential to be combined with trace soil evidence on clothing, to uncover the circumstances behind both current and unsolved criminal cases. However, simulations based on the casework circumstances would be required to interpret the observations.

Ultimately, for police with access to forensic laboratories fully equipped with XRD equipment and spectrophotometers, the value of soil transfer patterns on clothing lies in reconstructing the circumstances during and after an attack on a victim. By learning to visually identify trace soil patterns on clothing, police could recognise by an initial visual analysis alone, not only how the victim's body made contact with soil, but whether they were alive and struggling or incapacitated at the time. A subjective initial visual interpretation of events might then be objectively verified by a fully developed image processing software programme; with the capacity to create rose diagrams to map the directional data of each soil object transferred to fabric. The scenarios tested in this paper were kept as simple as possible to provide consistent and reproducible results; which, in turn, would aid the most accurate interpretation. The minimum size of soil objects identified in this paper was >2 pixel. More complex scenarios and a greater level of technical expertise when programming image processing software to identify trace soil evidence is required to better understand the full potential of this new method of forensic soil analysis.

5. Conclusions

Using a clothed human rescue-dummy, STEs conducted in the field analysed trace soil patterns from 'placing' and 'dragging' STEs using wet and dry anthropogenic and natural soil types at the Royal Tasmanian Botanical Gardens in Tasmania.

Forty eight (48) soil transfer experiments produced twelve transference patterns that were identified by an initial visual analysis and light microscopy and then objectively confirmed using image processing analysis. Five patterns were seen in 'dragging' STEs and two in 'placing' STEs with 100% consistency on two soil types at two sites.

No soil trails, embedded elongated fragments or damaged bra-fabric resulted from merely 'placing' the rescue dummy on soil because there was no movement of clothing across the soil surface.

Quantity of soil transferred depended primarily on the soil type and soil transfer method, but was also influenced by organic matter content, particle size, mineralogy and moisture content. During dragging STEs, a far greater quantity of soil was transferred to fabric than by merely placing the rescue dummy on the soil surface. The gravel-rich hard-packed anthropogenic soil type on the rose garden path at site 1 provided the highest quantity of wet soil transferred to fabric during dragging STEs. This was an increase of 63% from when the same soil was dry. Similarly, using the dark organic loamy-sand textured natural soil at site 2 we observed an increase of 41% in soil objects transferred to fabric when wet soil was used. During 'placement' STEs, both soils produced a low quantity of trace soil objects transferred to fabric. An increase was seen in both soils in the quantity of soil objects transferred when soil was wet, but results remained in the low category of soil objects transferred.

Using image processing methodology, in-depth quantifiable graphical presentations were provided on the quantity of soil transferred, the percentage of individual and aggregate soil objects transferred, directional patterns and a comparison of Munsell soil colours.

These field results provided practical evidence that trace soil patterns resulting from testing under controlled laboratory conditions were reproducible and easily identifiable using similar methods of soil transference, under realistic conditions in the field. All trace soil patterns documented in initial laboratory tests were also recognised in the field experiments. In this series of field experiments, three new trace soil patterns were also identified. By photographing the human rescue dummy 'in situ' at each simulated crime scene, a method was developed for forensic scientists to best capture this often subtle or faint forensic soil evidence on clothing before a body is transported for further analysis or clothing removed.

In this paper, dragging and placing were chosen as transfer mechanisms for investigation because of the issues relating to the lack of published research that would allow interpretation of trace soil patterns on a clothed victim during an Australian homicide case [22,23]. These two soil transfer methods commonly occur when a body when moved. We recognise that there are many other circumstances where soil can be transferred. However, in this paper, we have provided a methodology that can be used to evaluate case specific circumstances where tests can be done using similar soil and clothing.

The value of image processing is that it also allows evaluation of images of soil patterns that can be captured before a body is moved; which results in loss of soil evidence.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.forsciint.2017.03.026.

References

[1] R. Fitzpatrick, M. Raven, How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists, Soil Horiz. 53 (2012) 14–29, doi:http://dx.doi.org/10.2136/sh12-05-0016.
[2] R. Fitzpatrick, M. Raven, S. Forrester, 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, Springer Netherlands, Netherlands, 2009, pp. 105–127, doi: http://dx.doi.org/10.1007/978-1-4020-9204-6_8.
[3] R. Fitzpatrick, M. Raven, Soils, in: J. Siegel, P. Saukko (Eds.), Encyclopedia of Forensic Sciences, Second ed., Academic Press, Waltham, MA, 2013, pp. 206–212, doi:http://dx.doi.org/10.1016/B978-0-12-382165-2.00113-6.
[4] R. Fitzpatrick, Soil forensic analysis, in: A. Jamieson, A. Moenssens (Eds.), Wiley Encyclopedia of Forensic Science, 2013, doi:http://dx.doi.org/10.1002/9780470061589.fsa096.pub2 Chichester, West Sussex.
[5] R. Murray, Evidence from the Earth: Forensic Geology and Criminal Investigation, Second ed., Mountain Press Publishing, Missoula, MT, 2011.
[6] K. Pye, Geological and Soil Evidence: Forensic Applications, CRC Press, Boca Raton, FL, 2007.
[7] A. Ruffell, J. McKinley, Geoforensics, John Wiley & Sons, Ltd, Chichester, 2008.
[8] R. Morgan, P. Bull, Forensic geosciences and crime detection: identification, interpretation and presentation in forensic geoscience, Minerva Medicolegale. 127 (2007) 73–89.
[9] P. Bull, A. Parker, R. Morgan, The forensic analysis of soils and sediment taken from the cast of a footprint, Forensic Sci. Int. 162 (2006) 6–12, doi:http://dx.doi.org/10.1016/j.forsciint.2006.06.075.
[10] D. Stoney, A. Bowen, P. Stoney, Inferential source attribution from dust: review and analysis, Forensic Sci. Rev. 25 (2013) 107–142.
[11] E. Locard, Analyses of dust traces parts I, II and III, Am. J. Police Sci. 1 (1930) 276–298 (401-18, 96-514).
[12] S. McDermott, Trace evidence: transfer, persistence and value, in: J. Siegel (Ed.), Encyclopedia of Forensic Sciences, Second ed., Academic Press, Waltham, MA, 2013.
[13] P. Bull, R. Morgan, A. Sagovsky, G. Hughes, The transfer and persistence of trace particulates: experimental studies using clothing fabrics, Sci. Justice 46 (2006) 185–195, doi:http://dx.doi.org/10.1016/S1355-0306(06)71592-1.
[14] K. Aardahl, Evidential Value of Glitter Particle Trace Evidence, National University, San Diego, CA, 2003.
[15] K. Aardahl, S. Kirkowski, R. Blackledge, A target glitter study, Sci. Justice 45 (2005) 7–12, doi:http://dx.doi.org/10.1016/S1355-0306(05)71615-4.
[16] T. Hicks, R. Vanina, P. Margot, Transfer and persistence of glass fragments on garments, Sci. Justice 36 (1996) 101–107, doi:http://dx.doi.org/10.1016/S1355-0306(96)72574-1.
[17] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part I: fibre transference, J. Forensic Sci. Soc. 15 (1975) 17–27, doi:http://dx.doi.org/10.1016/S0015-7368(75)70932-5.
[18] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part II: fibre persistence, J. Forensic Sci. Soc. 15 (1975) 29–37, doi:http://dx.doi.org/10.1016/S0015-7368(75)70933-7.
[19] C. Pounds, K. Smalldon, The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. III: a preliminary investigation of the mechanisms involved, J Forensic Sci Soc. 15 (1975) 197–207, doi:http://dx.doi.org/10.1016/S0015-7368(75)70985-4.
[20] C. Roux, J. Robertson, Fibers, in: J. Siegel (Ed.), Encyclopedia of Forensic Sciences, Second ed., Academic Press, Waltham, MA, 2013.
[21] K. Nehse, Examination of fibers and textiles, in: A. Jamieson, A. Moenssens (Eds.), Wiley Encyclopedia of Forensic Science, John Wiley & Sons Ltd, Chichester, 2009, doi:http://dx.doi.org/10.1002/9780470061589.fsa161.
[22] B. Martin, The State of Western Australia v. Rayney. [No 3], WASC, 2012, pp. 1–369.
[23] B. Martin, Judgement Summary: The State of Western Australia v. Rayney. [No 3], WASC, 2012, pp. 1–13.

[24] R. Fitzpatrick, M. Raven, The State of Western Australia v. Lloyd Patrick Rayney Trial: Request for Supplementary Statement Relating to Extraction of Particulate Material from Bra, Centre for Australian Forensic Soil Science, 2012 p. 1–17.
[25] K. Murray, R. Fitzpatrick, R. Bottrill, R. Berry, H. Kobus, Soil transference patterns on bras: image processing and laboratory dragging experiments, Forensic Sci. Int. 258 (2016) 88–100, doi:http://dx.doi.org/10.1016/j.forsciint.2015.10.009.
[26] R. Isbell, National_Committee_on_Soils_and_Terrain. The Australian Soil Classification, 2nd ed., CSIRO Publishing, Clayton, Victoria, Australia, 2016.
[27] IUSS_Working_Group_WRB, World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No 106, FAO, Rome, 2014 , pp. 1–181. http://www.fao.org/3/a-i3794e.pdf.
[28] R. Fitzpatrick, Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use, in: F. Taha, M. Abdelfattah (Eds.), Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources, Springer, Netherlands, 2013, pp. 51–83, doi:http://dx.doi.org/10.1007/978-94-007-5332-7_2.
[29] Munsell_Color_Company, Munsell Soil Color, Book, Munsell Color X-rite, Michigan, 2009.
[30] S. Jantzi, J. Almirall, Characterization and forensic analysis of soil samples using laser-induced breakdown spectroscopy (LIBS), Anal. Bioanal. Chem. 400 (2011) 3341–3351, doi:http://dx.doi.org/10.1007/s00216-011-4869-7.
[31] Y. Marumo, Forensic examination of soil evidence, Natl. Res. Inst. Police Sci. 7 (2003) 95–111.
[32] R. Sugita, Y. Marumo, Validity of color examination for forensic soil identification, Forensic Sci. Int. 83 (1996) 201–210, doi:http://dx.doi.org/10.1016/S0379-0738(96)02038-5.
[33] R. Holcombe, GEOrient, School of Earth Sciences, University of Queensland, Queensland, Australia, 2011. http://www.holcombe.net.au/software/rodh_software_georient.htm.
[34] K. Murray, R. Fitzpatrick, R. Bottrill, R. Berry, R. Woolley, R. Doyle, et al., Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: laboratory dragging experiments, Acid Sulfate Soils Report No ASSC_096. Adelaide, The University of Adelaide, Australia, 2015, pp. 1–100. http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=34394;m=view.
[35] R. McDonald, R. Isbell, Soil Profile, Third ed., CSIRO Publishing, Melbourne, 2009.
[36] D. Correia, Using soil color anaysis for forensic application at a crime scene, Color & Science, Munsell Color, USA, 2017.
[37] Computer_Weekly_News, New forensic science study findings reported from Flinders University of South Australia (Soil transference patterns on bras: image processing and laboratory dragging experiments), Computer Weekly News, NewsRX LLC, USA, 2016.
[38] R. Fitzpatrick, M. Raven, P. Self, Clay mineralogy as significant evidence in 4 murder investigations involving a wide range of earth materials from Perth, Adelaide, Melbourne and Sydney, in: R.J. Gilkes (Ed.), Proceedings 23rd Australian Clay Minerals Society Conference, Perth : Australian Clay Minerals Society, 2014, pp. 23–26.
[39] W. Pelton, Distinguishing the cause of textile fibre damage using the scanning electron microscope (SEM), J. Forensic Sci. 40 (1995) 874–882, doi:http://dx.doi.org/10.1520/JFS15401J.
[40] W. Pelton, Use of SEM in textile forensic work, in: J. Hearle, B. Lomas, W. Cooke (Eds.), Atlas of Fibre Fracture and Damage to Textiles, Woodhead Publishing Limited, Cambridge, 1998, pp. 406–415.

4. CHAPTER 4 Soil transference patterns on clothing fabrics and plastic buttons: image processing and laboratory dragging experiments

This chapter investigates the influence which different fabric types can have on resulting trace soil patterns, when a simulated human body is dragged across twenty different soil types. Trace soil patterns are documented to indicate whether some patterns are universal across all fabrics tested.

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Name of Principal Author (Candidate)	Kathleen Murray		
Contribution to the Paper	I wrote the initial and subsequent drafts. These were edited by Rob Fitzpatrick and Hilton Kobus. XRD analysis included in this paper was undertaken by Ralph Bottrill.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	13/4/17

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i. the candidate's stated contribution to the publication is accurate (as detailed above);

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Forensic Science and Criminology

Research Article

Soil transference patterns on clothing fabrics and plastic buttons: Image processing and laboratory dragging experiments

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Abstract

An Australian homicide case in 2007 provided the catalyst for a series of soil transference experiments. Trace evidence of soil and brick particles on a victim's clothing provided evidence that the victim was initially attacked in her front yard and not where her body was buried. Police investigators hoped to use the patterns of soil and brick particles on the victim's clothing to prove the circumstances of the initial attack and the method by which the victim's body was moved. However during court proceedings, it became apparent that no relevant scientific literature existed that would enable forensic investigators to recognise or interpret trace soil patterns on clothing.

In response, methodology to study soil transference was designed to enable distinctive trace soil patterns on bra fabric to be identified and categorised. In this paper, the new methodology involving visual observation, digital photography of the soil patterns and image processing software is applied to test the influence of four common clothing fabrics on the abundance of soil transferred and the patterns produced. The clothing fabrics tested involved cotton, nylon, polyester-cotton and polar fleece (polyester brushed both sides), clothing seams and buttons. The soil types tested were expanded to twenty different soils to better understand the influence of soil type, moisture content and clay fraction (<2 μm) mineralogy on soil transfer patterns. Experiments simulated a clothed human body dragged across different natural and anthropogenic soil surfaces, under both wet and dry conditions in the laboratory.

Introduction

Forensic soil scientists have a range of sophisticated analytical techniques available to compare soil with possible places of origin [1-9]. Their expertise has provided compelling evidence in criminal investigations; especially when forensic soil evidence strongly associates a suspect with a victim or crime scene [1]. For example, in a Western Australian homicide trial in 2012, which was before a judge only, the judge concluded that the mineralogy data from the brick particles on the victim's clothing and the bricks from her front driveway [10,11] suggested she was initially attacked in her front yard and not at Kings Park where her body was buried [12,13]. However, an important question raised during the trial and by the judge was the method by which the brick particles were transferred to the victim's clothing [12,13]. During court proceedings, it became apparent that no research specific to identifying or interpreting soil transfer patterns on clothing existed and that there was a need for systematic studies to determine whether soils deposited by dragging produced characteristic features that could identify this method of transfer [14].

This led to the work reported in the first two papers in this series by Murray et al. [15,16] on transfer patterns produced when clothing comes into contact with soil due to a dragging motion or by placing the clothing on soil with no movement. The methodology involved visual observation and digital photography of the soil patterns. Image processing software was adapted to analyse the digital photographs of the trace soil patterns to provide an objective methodology for determining the characteristics caused by dragging.

The objective of the work reported in this paper was to apply the methodology of Murray et al. [15] to discover the extent that wider fabric types could influence resulting trace soil patterns on clothing from a broader range of soil types. Soil transfer experiments will be conducted under similar laboratory conditions as original experiments to the following four common fabrics: (i) cotton, (ii) cotton-polyester, (iii) nylon and polar fleece (polyester brushed both sides), and (iv) seams and buttons.

Materials and methods

Soil samples

Soil diversity enables forensic soil experts to differentiate soil from different locations by its range of crystalline minerals and organic matter, as well as trace amounts of manufactured materials such as brick fragments and road gravel [1-7]. Variations in soil colour provide one of the most distinguishing characteristics of trace soil evidence

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[17] and is routinely identified by agricultural [18] and forensic soil scientists [19] working in the field or laboratory using the standard Munsell soil colour system [20].

Twenty anthropogenic, human-altered or human-transported (HAHT) soils and natural soil types originated from three sources in Tasmania, Australia (Figure 1): (i) the University of Tasmania (UTas) Research Farm on Richmond Rd, Cambridge, (ii) Pinnacle Rd, Mount Wellington and (iii) the Royal Tasmanian Botanical Gardens (RTBG), Lower Domain Rd, Hobart.

The soil classifications used in this paper incorporate international and national general-purpose classifications as well as a local special-purpose soil classification system (Table 1) so as to be of global relevance to the greatest number of forensic investigators and researchers. Detailed soil morphological descriptions and classifications including carbon content, mineralogy (by X-ray diffraction) and pH is detailed in Murray et al. [15,21] and summarised in Table 1.

Experimental design

Dragging experiments: The dragging method used was adapted from previous Murray et al. [15] laboratory soil transference experiments (STE's) that dragged weighted bras across seven soil types under both wet and dry conditions. A glass Pyrex 3 qt/2.8 L dish was filled >3 cm with bulk soil. The non-slip mat and heavy weights on one side ensured the dish did not move during experiments. A smooth-surfaced 2 kg weight with a yellow 'drag line' was enclosed in a tightly-fitted plastic bag, enabling easy cleaning between STEs. 30 cm² fabric squares had a raised seam sewn down the middle; to replicate seams joining sections of clothing fabric together. Half of the cotton squares also had a 1 cm plastic button sewn onto them. White fabric enabled easy detection of trace soil transferred.

A fabric square was secured to the weight by a strong rubber-band and each fabric square was dragged in timed three second runs through wet or dry soil using the drag line (Figure 2). The attached weight stabilised soil transfer patterns during analysis. A minor difference from initial experiments [15] was that the fabric squares were not secured so tight as to inhibit creases or folding of clothing fabric that might realistically occur if a clothed victim was dragged across a soil surface [16].

Munsell soil colour [20] and trace soil 'patterns' on fabric were measured using the image processing method developed by Murray et al. [15]. This method could enable a crime scene photographer equipped with a basic digital camera, a standard white scale bar and computer with image processing software to analyse forensic soil evidence with minimal training. The methodology was purposefully kept as simple as possible to allow an objective scientific analysis of forensic soil evidence to be within reach of all police departments, regardless of funding, resources or geographic location. To test the ability of image processing software to analyse digital photographs taken under less than optimal lighting conditions, STEs were photographed under artificial lighting and not first moved into natural sunlight, as recommended by Munsell [20].

Image processing data on directionality was entered into GEOrient version 9.5.0 [26] to produce rose Diagrams of trace soil patterns for quick and clear comparisons.

Trimble eCognition Developer image processing of photographs of the trace soil patterns on fabric was used to:

- Confirm patterns observed visually by human eye,
- Provide standardised numerical data of the colour and shape of soil objects ≥100 µm/2 pixel,

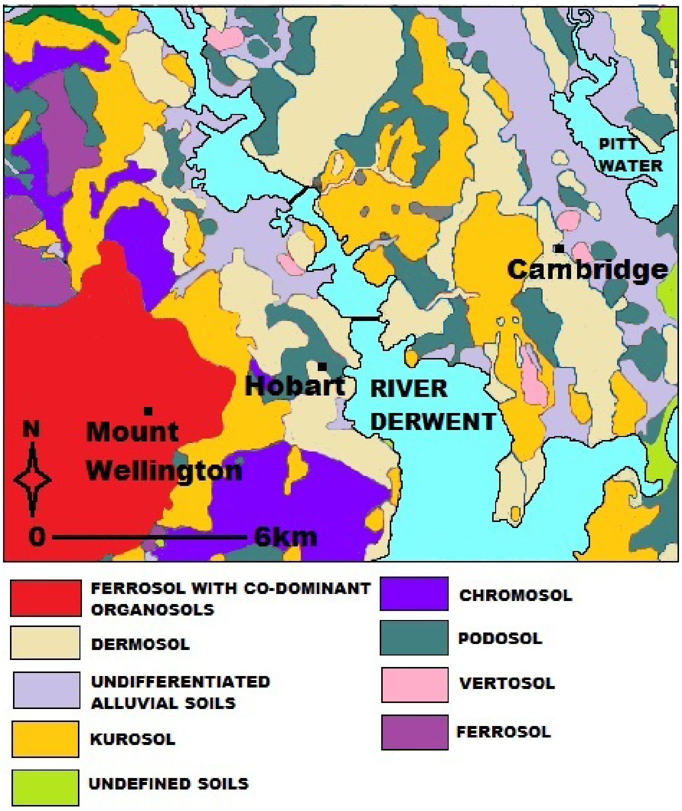


Figure 1. Soil map encompassing the three soil site locations in Tasmaniaat Mount Wellington, Hobart and Cambridge [22].

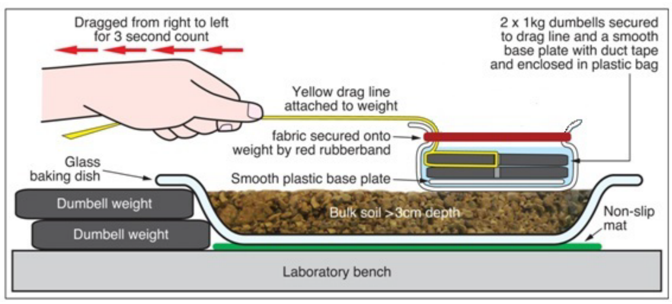


Figure 2. Photograph (above) and cross-section of weighted fabric dragged from right to left over soil material during a three second count Soil Transference Experiment (STE). The glass dish containing soil was on a nonslip mat with a backstop of weights on the left to prevent movement during the STE (modified from Murray et al. [15]).

Table 1. Soil morphology, Australian Soil Classification of soil materials [23] and the approximate corresponding World Reference Base for Soil resources class [24].

Locality (depth cm)	**Centre for Australian Forensic Soil Science (CAFSS) code**	**Munsell[1] Soil Colour fine <2 mm (wet)** (dry)	**Soil type[2]**	**Brief description**	**The Australian soil classification**	**The world reference base for soil resources (WRB)**
Site 1: UTas farm horizon 1 (0-10cm)	110.1.1	**Very dark brown 10YR 2/2** Dark grayish brown 10YR 4/2	Duplex soil with nonrestricted clayey subsoil	Gravel (50%); clayey sand, water repellent, 6.92% Carbon (C).	Humose, Mesotrophic, Brown Chromosol; medium, moderately gravelly, loamy, clayey, moderate	Haplic, Luvisol (Clayic, Cutanic)
Site 1: UTas farm horizon 2 (15-30cm)	110.1.2	**Very dark brown 10YR 2/2** Brown 10YR 5/3	As above	Gravel (45%); sandy loam, water repellent, 2.46% Carbon (C).	As above	As above
Site 1: UTas farm horizon 3 (40-60cm)	110.1.3	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	As above	Gravel (90%); heavy clay, non-water repellent, 0.92% Carbon (C).	As above	As above
Site 1: UTas farm horizon 4 (60-80cm)	110.1.4	**Strong brown 7.5YR 5/6** Reddish yellow7.5YR 6/6	As above	Gravel (90%); medium-heavy clay, non-water repellent, 0.26% Carbon (C).	As above	As above
Site 1: UTas farm horizon 5 (80-100cm)	110.1.5	**Dark brown 7.5YR 3/4** Reddish yellow 7.5YR 6/6	As above	Gravel (40%); clayey sand, non-water repellent, 0.19% Carbon (C).	As above	As above
Site 2: UTas farm horizon 1 (0-17cm)	110.2.1	**Very dark brown 10YR 2/2** Grayish brown 10YR 5/2	Duplex soil with restricted sodic clayey subsoil	Gravel (35%); sandy loam, non-water repellent, 2.61% Carbon (C).	Vertic, Mottled-Mesonatric, Brown Sodosol; medium, moderately gravelly, loamy, clayey, deep	Vertic, Abruptic Solonetz (Albic, Hypernatric)
Site 2: UTas farm horizon 2 (17-34cm)	110.2.2	**Brown 10YR 4/3** Pale brown 10YR 6/3	As above	Gravel (95%); medium-heavy clay, non-water repellent, 1.14% Carbon (C).	As above	As above
Site 3: UTas farm horizon 1 (0-10cm)	110.3.1	**Very dark gray 10YR 3/1** Dark grayish brown 10YR 4/2	Poorly structured cracking clay	Gravel (90%); medium clay, water repellent, 2.37% Carbon (C).	Endocalcareous, Massive, Brown Vertosol; very gravelly, fine, very fine, deep	Calsic, Vertisol (Gilgaic, Gleyic)
Site 3: UTas farm horizon 2 (20-40cm)	110.3.2	**Yellowish brown 10YR 5/4** Grayish brown 10YR 4/2	As above	Gravel (97%); heavy clay, non-water repellent, 0.84% Carbon (C).	As above	As above
Site 3: UTas farm horizon 3 (40-70cm)	110.3.3	**Light yellowish brown 10YR 6/4** Light gray 10YR 7/2	As above	Gravel (90%); medium clay, non-water repellent, 3.54% Carbon (C).	As above	As above
Site 3: UTas farm horizon 4 (70-110cm)	110.3.4	**Yellowish brown 10YR 5/4** Brown 10YR 5/3	As above	Gravel (90%); heavy clay, non-water repellent, 0.44% Carbon (C).	As above	As above
Locality (depth cm)	**Centre for Australian Forensic Soil Science (CAFSS) code**	**Munsell[1] Soil Colour fine <2mm (wet)** (dry)	**Soil type[2]**	**Brief description**	**The Australian soil classification**	**The world reference base for soil resources (WRB)**
Site 4: Mount Wellington horizon 1 (0-10cm)	110.4.1	**Very dark brown 10YR 2/2** Very dark grayish brown 10YR 3/2	Well structured clayey soil with boulders	Gravel (70%); sandy clay loam, water repellent, 12.8% Carbon (C).	Humose-Mottled, Placic, Brown Kandosol; medium, moderately gravelly, loamy, clayey, deep	Xanthic, Ferretic, Ferralsol (Clayic, Colluvic)
Site 4: Mount Wellington horizon 3 (40-60cm)	110.4.3	**Strong brown 7.5YR 4/6** Brownish yellow 10YR 6/6	As above	Gravel (70%); sandy clay loam, non-water repellent, 0.96% Carbon (C).	As above	As above
Site 4: Mount Wellington horizon 5 (110-140cm)	110.4.5	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	As above	Gravel (75%); sandy clay loam, non-water repellent, 0.34% Carbon (C).	As above	As above
Site 5: rose garden path (0-10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	Anthropogenic gravelly sandy loam soil	Gravel (90%; arkosic sandstone and andesitic-to-weathered mafic igneous rock) loamy sand, water repellent, 0.7% Carbon (C).	Spolic anthroposol, very gravelly, sandy, very shallow	[3]Spolic technosol (Densic)

Site 6: brick fragments (0-2 cm)	110.6.2	**Red 2.5YR 5/8** Light red 2.5YR 7/8	Anthropogenic brick fragment-rich soil	Gravel (90%), sandy, water repellent, weathered brick fragments (0.5-4 cm),1.2% C.	Urbic anthroposol, very gravelly, sandy, very shallow	[3]Urbic Ekranictechnosol (Transportic)
Site 7: rose garden bed (0-10 cm)	110.7.1	**Black 10YR 2/1** Black 7.5YR 2.5/1	Anthropogenic, organic-rich sandy loam soil	Gravel (15% coarse river sand), loamy sand (25%), water repellent, 30% fine compost, 30% composted pine bark, 14% C.	Hortic anthroposol non-gravelly, sandy, shallow	Horticanthrosol(Escalic)
Site 8: Japanese garden bed (0-10 cm)	110.8.1	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	Anthropogenic, quartz-rich, gravelly, sandy soil	Gravel (90%: ~80% rounded quartz, 10% sub-rounded to angular dolerite;5% ironstone), loamy sand, water repellent, 3% C.	Spolic anthroposol, very gravelly, sandy, very shallow	[3]Spolic technosol (Grossartefactic, Transportic)
Site 9: south eastern boundary horizon 1 (5-0 cm)	110.9.1	Leaves not analysed for Munsell soil colour by naked eye	Natural organic-rich soil	Undecomposed Leaves (60%) and decomposed (40%)	Humose, mesotrophic, Brown Dermosol, non-gravelly, sandy, deep	EutricCambisol (Humic)
Site 9: south eastern boundary horizon 2 (0-10 cm)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	Natural loamy soil	Gravel (2%), loamy sand, water repellent, 23% C.	As above	As above

Where:
[1]Munsell soil colour [20]: measured on the fine earth fraction (<2 mm).
[2]Special-purpose technical soil classification system [25], which uses plain English and places strong emphasis on being either an anthropogenic soil or natural soil, the soil texture (e.g. gravelly, sandy, sandy loam) and the presence of high quantities of organic carbon (>10%; organic-rich).
[3]Classification of technosols [24]: Connotation: soils dominated or strongly influenced by human-made material; from Greek *technikos*, skilfully made. They contain a significant amount of *artefacts*.
[4]Classification of Anthroposol [24]: Connotation: soils with prominent characteristics that result from human activities; from Greek *anthropos*, human being (e.g. such as addition of organic material and cultivation).
[5]Classification of natural soils: Connotation: soils with substantial soil formation such as Dermosols [23] or Cambisols [24].

Table 2. Trace soil patterns identified on fabric using 'dragging' as the transfer method.

	Soil transfer pattern	Symbol used	Figure	Location on fabric	Contributing soil characteristic
1	Soil 'trails'	red circle	Figure 3 Figure 4 Figure 5	parallel to direction of movement	Greater quantity of wet soil objects transferred than dry
2	Soil accumulated on raised surfaces	yellow circle	Figure 3 Figure 4	raised middle seams perpendicular to direction of movement	no consistent trends
3	Fold and crease marks	green circle	Figure 3 Figure 4	approx. parallel to direction of movement	no consistent trends
4	Damaged or frayed fabric	purple circle	Figure 4	where fabric has caught on hard surface soil objects	hard gravel-textured soil
5	Soiled water stains	blue circle	Figure 4	sporadically where fabric had made contact with soil surface	wet soil
6	Elongated particles aligned and/or embedded	orange circle	Figure 3 Figure 4	embedded in or on fabric parallel to direction of movement	no consistent trends
7	Speckling of soil on fabric	_	Figure 4	sporadically where fabric had made contact with soil surface	no consistent trends
8	Dusted' plastic buttons	pink circle	Figure 5	buttons sewn onto cotton fabric (no other fabrics had buttons)	very dry soil
9	Muddy clumps on wet shiny plastic buttons	_	Figure 5	buttons sewn onto cotton fabric	wet soil
10	Elongated scratches on plastic buttons	black circle	Figure 5	buttons sewn onto cotton fabric	Greater occurance on dry soil than wet soil

- Allow statistical comparison of observed soil patterns.

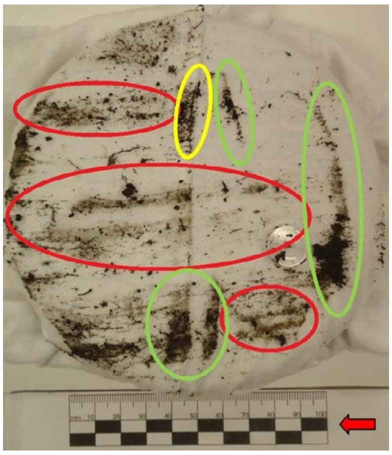
This included quantity and directionality of soil transferred, percentage of individual soil objects and aggregates and Munsell soil colour range. However, the primary focus of this paper was to investigate whether new or previously documented trace soil patterns identified by Murray et al. [15,16] could be identified on different fabric types; by visual analysis or through use of image processing software.

Limitations in software programming were overcome by disregarding soil objects <100 µm. Difficulties differentiating mineral from organic soil objects could feasibly be overcome with more complex programming. Full details of this method are provided in Murray et al. [15,21].

Results

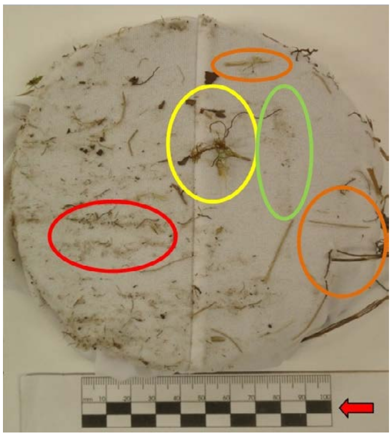
Trace soil patterns documented on fabric using transfer method of 'dragging'

Ten patterns were identified in soil transferred onto the weighted fabric squares (Table 2). Six of the ten patterns were seen in all 20 soil types (Figures 3-6). Soil transfer pattern numbers 1, 2, 4 and 6 were originally documented in laboratory experiments by Murray et al. [15] Pattern numbers 3, 5 and 7 were first documented in field experiments by Murray et al. [16] The final three patterns involving plastic buttons are new patterns, never before documented.



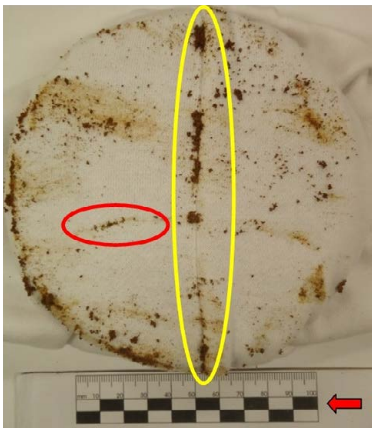
(A)WET nat. quartz and organic-rich soil (site 4 horizon 1): cotton

Figure 3(A). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Direction of movement = right to left). Red circles = soil trails; yellow circles = soil build upon or in front of raised seam; green circles = fold marks delineated by soil.



(B) DRY natural quartz-rich soil (site 1 horizon 1): nylon

Figure 3(B). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Direction of movement = right to left). Red circles = soil trails; yellow circles = soil build upon or in front of raised seam; green circles = fold marks delineated by soil; orange circles = elongate organic soil objects aligned with direction of movement.

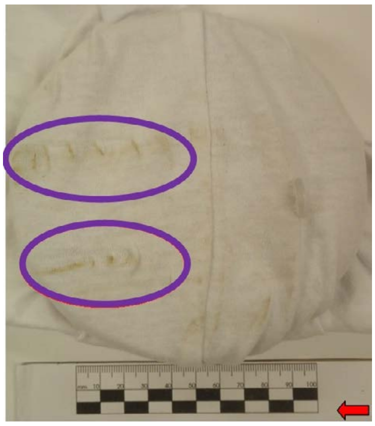


(C)WET nat. quartz-rich soil (site 4 horizon 3): poly-cotton

Figure 3(C). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Direction of movement = right to left). Red circles = soil trails; yellow circles = soil build upon or in front of raised seam.

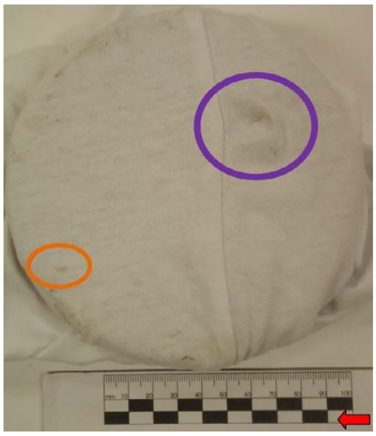
(D) WET nat. quartz-rich soil (site 2 horizon 2): polar fleece

Figure 3(D). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Direction of movement = right to left). Green circles = fold marks delineated by soil.



(A) DRY natural quartz-rich soil (site 2 horizon 2): cotton

Figure 4(A). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Direction of movement = right to left). Purple circle = fabric damaged or gouged by hard or gravel-rich soil surface.



(B) DRY natural quartz and smectite-rich soil (site 3 horizon 1): cotton

Figure 4(B). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Direction of movement = right to left). Orange circle = elongate organic soil object (grass seed) aligned with direction of movement and or embedded in fabric; purple circle = fabric damaged or gouged by hard or gravel-rich soil surface.

(C) WET anthropogenic quartz gravel-rich soil (site 8): nylon

Figure 4(C). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Direction of movement = right to left). Blue circle = water marks; green circle = fold marks delineated by soil.

(D) DRY anthrop. quartz and organic-rich soil (site 7):polar fleece

Figure 4(D). Trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Direction of movement = right to left). Yellow circle = soil building up in front or on top of raised seam.

(A)DRY nat. organic-rich leaves (site 9 horizon 1): cotton

Figure 5(A). Trace soil patterns on buttons using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Photomicrographs display direction of movement = left to right). Button shows 'dusting' of very fine soil objects (pink circles).

(B) WET nat. smectite-rich soil (site 1 horizon 3): cotton

Figure 5(B). Trace soil patterns on buttons using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Photomicrographs display direction of movement = left to right). Wet soil has built up on leading (right) edge and underneath button.

(C)DRY natural quartz-rich soil (site 1 horizon 2): cotton

Figure 5(C). Trace soil patterns on buttons using the transfer method of dragging weighted fabric for a three second count across a soil bed containing dry soil. (Photomicrographs display direction of movement = left to right). Button displays horizontal scratches (black circle) and dusting of soil along scratch lines. Horizontal scratches on the surface of this plastic button indicates dragging as the method of soil transfer.

(D) WET nat. smectite& quartz-rich soil (site 3 horizon 2): cotton

Figure 5(D). Trace soil patterns on buttons using the transfer method of dragging weighted fabric for a three second count across a soil bed containing wet soil. (Photomicrographs display direction of movement = left to right). Button displays horizontal scratches (black circles) and wet soil has built up on leading (right) edge and underneath button. Horizontal scratches on the surface of this plastic button indicates dragging as the method of soil transfer.

Directionality of soil objects transferred, analysed by soil and fabric type and seams

Using image processing directional numerical data, quick and simple rose diagrams [26] mapped directionality of thousands of dry or wet soil particles ≥2 pixels diameter transferred onto fabric (Figure 6 and Figure 7). This not only provided an objective confirmation of naked eye interpretation of trace soil directionality, but was accurate enough to detect directionality of thousands of soil objects down to 100 μm diameter. Fabric type did not reveal a consistent influence on soil objects transferred. Soil mineralogy (in particular the amount of smectite in the clay fraction (<2 um) and soil moisture content had a greater influence on resulting trace soil patterns. Fabric seams and buttons also had a definite influence on trace soil patterns produced.

Strong uni-modal directionality was displayed when fabric was dragged in one direction across soil. On the rose diagrams, black directional lines reaching the edges of the rose diagram show the directions with the greatest number of soil objects aligned. In most of the images, there was a strong horizontal line indicating direction of drag from right to left. This is particularly the case when wet soil was transferred to fabric.

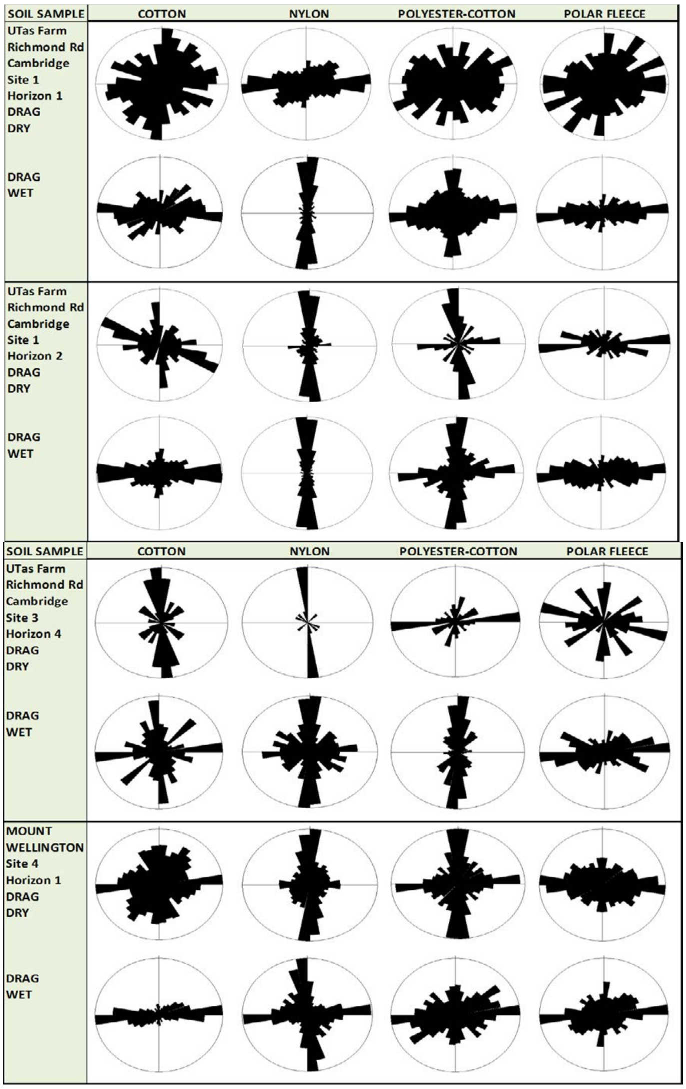


Figure 6. Rose diagrams indicate directionality of dry and wet soil transferred from site 1 horizons 1 and 2 and site 3 horizon 4 from UTas farm. Site 4 horizon 1 from Mt Wellington is also displayed. Numerical data from two digital photographs are combined in each rose diagram. Direction of movement = right to left.

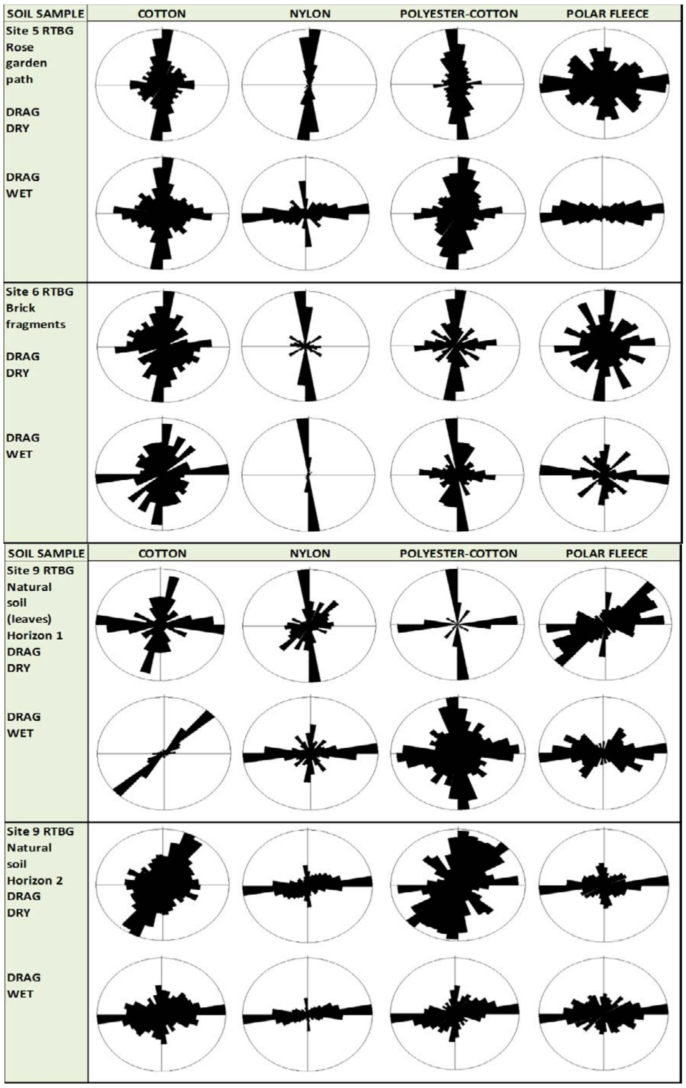


Figure 7. Rose diagrams display directionality of dry and wet soil transferred onto fabric from sites 5, 6 and 9 (two horizons) at RTBG. Strong uni-modal directionality was produced when fabric was dragged right to left across soil. Dry soil objects more than wet soil tended to gather against the middle seam, creating more bi-modal directionality. Numerical data from two digital photographs are combined in each rose diagram. (Direction of movement = right to left).

In other rose diagrams, loose soil objects gathered against the raised middle seam to produce a strong uni-modal vertical (or bi-modal cross-like) directionality. This tended to occur when dry soil was transferred. In cases where very minute traces of soil were transferred (such as site 9: natural soil horizon of undecomposed leaves), microscopic soil objects tended to be found pushed against the middle raised seam, creating a uni-modal vertical directionality.

Dry soil also tended to have a higher quantity of loose soil objects scattered more randomly over fabric. The lack of directionality that very dry friable soil displayed, was reminiscent of rose diagrams created by placing fabric on soil [16]. This transfer pattern is documented in rose diagrams produced using dry soil from UTas farm site 1 and 3 and brick fragments from RTBG (Figure 6 and Figure 7).

Different horizons from the same soil profile produced very different modes of directionality. Natural surface soil at UTas site 1 (horizon 1) had a granular structure and clayey-sand texture. This soil produced a more random directionality than the undisturbed lower horizon 2 with a granular to sub-angular blocky soil structure and sandy-loam texture. When both soils were wet, there was a strong uni-modal to bi-modal directionality to soil particles transferred. UTas site 3 (horizon 4) had a similar granular-to-angular blocky structure which was combined with a heavy clay texture. Directionality results using this wet and dry soil type were similar to soil from UTas site 1 (horizon 2).

Natural surface soil at Mt Wellington (site 4 horizon 1) had a massive structure and sandy-clay-loam texture. A greater quantity of soil objects was transferred under dry conditions than wet. On the rose diagram, this was indicated by the thicker black section in the middle of the rose diagram; as multiple loose soil objects scattered in a full spectrum of directions. Despite this, there was still a uni-modal to bimodal directional trend, which was indicated by black lines on the rose diagram reaching to the very edges in a horizontal and/or vertical direction.

Gravel-rich rose garden path soil at site 5 RTBG (Figure 7) had a granular-to-single grain structure with a loamy-sand textured matrix.

Brick fragments at site 6 shared a similar gravel-rich structure and produced very similar directionality results.

Natural soil on the SE boundary of RTBG had two horizons analysed for directionality (Figure 7). The surface layer of undecomposed leaves (horizon 1) showed minimal trace soil transferred. However, a strong uni-modal to bi-modal directionality was still recorded. Underlying natural mineral soil (horizon 2) transferred a greater quantity of trace soil to fabric. Using this dry soil, a larger quantity of loose soil objects was gathered against the perpendicular seam of cotton and polyester-cotton fabrics than seen using nylon and polar fleece fabrics.

Quantity of soil objects transferred to fabric analysed by soil type

Quantity of soil objects transferred to fabric was measured by image processing analysis using digital photographs taken of each STE. Image processing of digital photographs taken of individual and aggregate soil objects transferred onto fabric provided an objective approach to graphically present soil transfer patterns. Quantitative graphical presentation of soil patterns, including texture, mineralogy, chemistry, moisture content, quantity and directionality of soil transferred, added standardised objectivity not possible through identification by naked eye alone. Image processing numerical data is summarised in Figure 8 and Table 3.

Soils were grouped by location and soil moisture content. Numerical data for individual and aggregate soil objects transferred from each soil sample to fabric, were combined and averaged.

Soil objects covering > 0.5 million pixels were classified as being a low quantity of soil transferred to fabric.

Soil objects covering 0.5 million to >1 million pixels were classified as a moderate quantity of soil transferred.

Soil objects covering 1 million pixels and higher were classified as a high quantity of soil transferred.

Using image processing numerical data that measured the quantity of trace soil objects (individual and aggregates) transferred to fabric, the following associations between soil types, clay mineral properties (smectite) and soil moisture content was discovered:

- Natural quartz and smectite-rich soil (site 1: UTas farm, horizons 1 to 5; Table 3) with 0 to 12% organic content, produced a low quantity of light gray soil objects when transferred to fabric when dry and increasing to a moderate to high quantity when wet (light gray to very dark brown).
- Natural quartz-rich soil (site 2: UTas farm, horizons 1 to 2) with low organic content, produced a low quantity of light gray soil objects when transferred dry to fabric and increasing to a moderate quantity when wet (light gray).
- Natural smectite and quartz-rich soil (site 3: UTas farm, horizons 1 to 4) with low organic content (note: horizon 3 had 21% calcite) produced a low quantity of light gray soil particles when transferred dry to fabric and increasing to moderate quantity when wet (light gray).

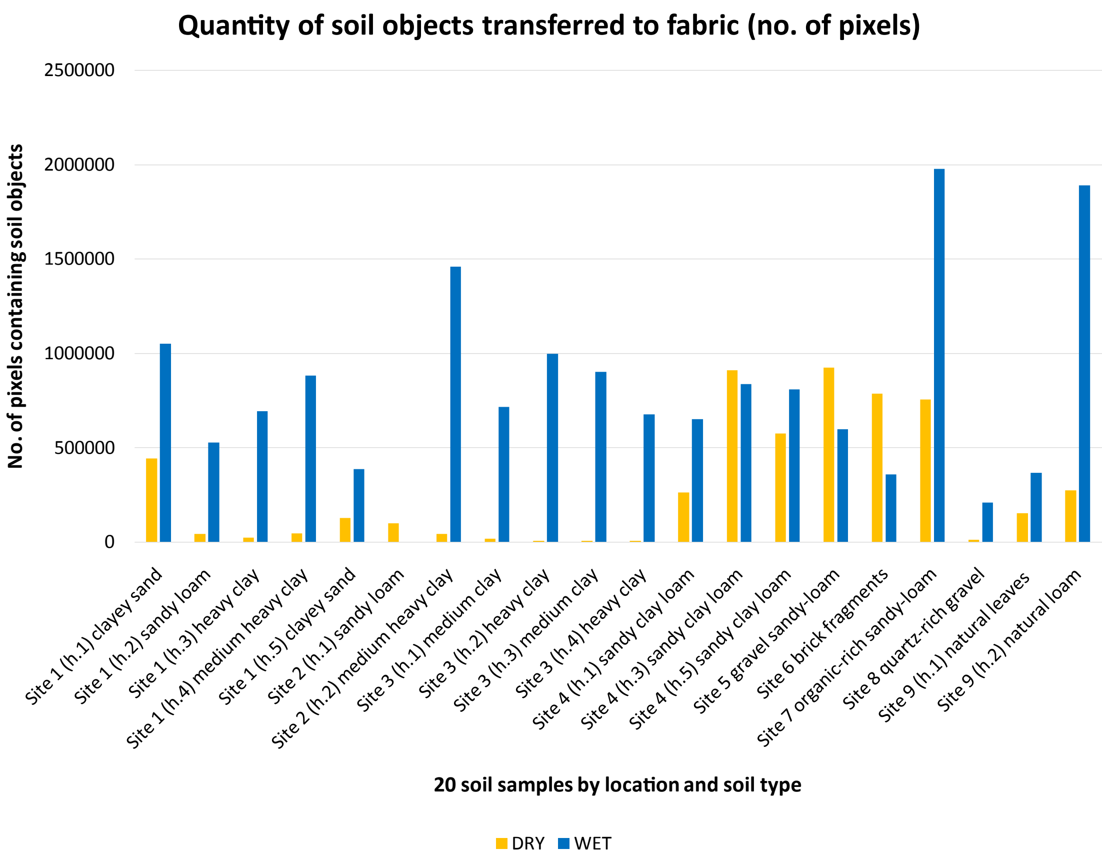


Figure 8. Quantity of soil transferred to fabric, analysed by number of pixels in digital photographs that contained individual or aggregate soil objects. Image processing numerical data is subdivided by location and soil moisture content.

Table 3. Summary of soil data using naked eye, image processing, XRD and NDIR analysis of the seven soil types and trace soil transferred to fabric [21].

Locality	**Centre for Australian Forensic Soil Science (CAFSS)**	**Munsell¹ soil colour <2 mm fraction**	**Dominant trace soil²Munsell colour**	**Ave. soil transferred (individual + aggregates) in pixels³**		**Weight % Clay content (Smectite)**	**% Organic content**	**% Gravel content**
(Depth cm)	**code**	**(wet)** (dry)	**(wet)** (dry)	**(wet)** (dry) **High quantity** **Moderate** **Low**	**(H)** **(M)** **(L)**			
Site 1: UTas farm horizon 1 (0-10 cm)	110.1.1	**Very dark brown 10YR 2/2** Dark grayish brown 10YR 4/2	**Very dark brown 7.5YR 2.5/2** Light gray 10YR 7/2	**1052138** 442082	**(H)** (L)	5 ± 1	6.92	50
Site 1 horizon 2 (15-30cm)	110.1.2	**Very dark brown 10YR 2/2** Brown 10YR 5/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**526340** 41055	**(M)** (L)	13 ± 2	2.46	45
Site 1 horizon 3 (40-60cm)	110.1.3	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**692803** 23437	**(M)** (L)	56 ± 5	0.92	90
Site 1 horizon 4 (60-80 cm)	110.1.4	**Strong brown 7.5YR 5/6** Reddish yellow 7.5YR 6/6	**Light gray 7.5YR 2.5/2** Light gray 10YR 7/2	**882729** 44044	**(M)** (L)	59 ± 5	0.26	90
Site 1 horizon 5 (80-100 cm)	110.1.5	**Dark brown 7.5YR 3/4** Reddish yellow 7.5YR 6/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**386965** 125753	**(L)** (L)	52 ± 5	0.19	40
Site 2: UTas farm horizon 1 (0-17 cm)	110.2.1	**Very dark brown 10YR 2/2** Grayish brown 10YR 5/2	no image data available Light gray 10YR 7/2	no image data available 98056	(M)	3 ± 1	2.61	35
Site 2 horizon 2 (10-34 cm)	110.2.2	**Brown 10YR 4/3** Pale brown 10YR 6/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**1461174** 43375	**(H)** (L)	5 ± 2	1.14	95
Site 3: UTas farm horizon 1 (0-10 cm)	110.3.1	**Very dark gray 10YR 3/1** Dark grayish brown 10YR 4/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**715203** 16573	**(M)** (L)	41 ± 4	2.37	90
Site 3 horizon 2 (20-40 cm)	110.3.2	**Yellowish brown 10YR 5/4** Grayish brown 10YR 5/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**996395** 4256	**(M)** (L)	58 ± 5	0.84	97
Site 3 horizon 3 (40-70 cm)	110.3.3	**Light yellowish brown 10YR 6/4** Light gray 10YR 7/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**900580** 4230	**(M)** (L)	46 ± 4	3.54	90
Site 3 horizon 4 (70-110 cm)	110.3.4	**Yellowish brown 10YR 5/4** Brown 10YR 5/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**675637** 4459	**(M)** (L)	64 ± 5	0.44	90
Site 4: Mount Wellington horizon 1 (0-10 cm)	110.4.1	**Very dark brown 10YR 2/2** Very dark grayish brown 10YR 3/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**651041** 262720	**(M)** (L)	7 ± 2	12.8	70
Site 4 horizon 3 (40-60 cm)	110.4.3	**Strong brown 7.5YR 4/6** Brownish yellow 10YR 6/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**837508** 910006	**(M)** (M)	10 ± 2	0.96	70
Site 4 horizon 5 (110-140 cm)	110.4.5	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**809442** 574757	**(M)** (M)	5 ± 2	0.34	75
Site 5: RTBG rose garden path (0-10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**596435** 925693	**(M)** (M)	19 ± 3	0.70	90
Site 6: RTBG brick fragments (0-2 cm)	110.6.2	**Red 2.5YR 5/8** Light red 2.5YR 7/8	**Light gray 10YR 7/2** Light gray 10YR 7/2	**358527** 785580	**(L)** (M)	Trace of Mullite	0.29	90
Site 7: RTBG rose garden bed (0-10 cm)	110.7.1	**Black 10YR 2/1** Black 7.5YR 2.5/1	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**1977927** 755414	**(H)** (M)	2 ± 1	14.0	15
Site 8: RTBG Japanese garden bed (0-10 cm)	110.8.1	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**209871** 11683	**(L)** (L)	2 ± 1	3.10	90

Site 9: RTBG SE boundary horizon 1 (5-0 cm above surface)	110.9.1	**Leaves** leaves	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**367741** 150810	**(L)** (L)	No XRD analysis	No NDIR analysis	Leaves
Site 9 horizon 2 (0-10 cm)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**1891918** 272163	**(H)** (L)	20 ± 3	22.8	2

Where: [1]Munsell Soil Colour [20]: measured by naked eye on the fine earth fraction (<2mm).
[2]Munsell Soil Colour measured by image processing software from two digital photographs of trace soil on fabric.
[3]Average of two STEs tested using either wet or dry soil sample.
[4]XRD analysis of % weight clay (Smectite) content in homogenous bulk soil sample.
[5]NDIR analysis of organic content of homogenous bulk soil sample.
[6]Estimate by naked eye alone using method of McDonald and Isbell [28].
[7]Image data not available for this source digital photograph because the current manual method of clicking on each image to be analysed, led to this accidental omission due to human error.

- Natural quartz-rich soil (site 4: Mt Wellington), with organic-rich horizon 1, and kaolinite, gibbsite and goethite-rich horizons 3 and 5, produced a low to moderate quantity of light gray soil objects when transferred dry to fabric and increasing to moderate quantity when wet (light gray).

- Anthropogenic, gravelly, sandy loam soil (site 5: rose garden path) with low organic carbon content, produced a moderate quantity of light gray soil objects when transferred to the fabric when dry and increasing (but staying within) the moderate quantity when wet (light gray).

- Anthropogenic brick fragment-rich soil (site 6: brick fragments) with high quartz and negligible organic and smectite content, produced a moderate quantity of light gray soil objects when transferred to fabric when dry, decreasing to a lower quantity when wet (light gray).

- Anthropogenic, organic-rich sandy loam soil (site 7: rose garden bed) with approximately 15 to 19% smectite and high amounts of arkosic sandstone and andesitic-to-weathered mafic igneous rock produced a moderate quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to a high quantity when wet (very dark brown).

- Anthropogenic, quartz-rich gravelly sandy soil (site 8: Japanese garden bed) with high quartz content and negligible organic and smectite content, produced a low quantity of very dark brown soil objects to fabric when dry, increasing (but remaining within) a low quantity when wet (very dark brown).

- Natural organic-rich soil (site 9: horizon 1 organic-rich soil) with very high organic carbon content (undecomposed leaves), produced a low quantity of very dark brown soil particles when transferred to the fabric when dry and increasing (but remaining within) a low quantity when wet (very dark brown).

Natural loamy soil (site 9: underlying mineral soil) with approximately 20% smectite produced a low quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to high quantity when wet (very dark brown). This is because smectite is highly responsive to soil moisture and soils with high smectite content can undergo as much as a 30% volume change; an indication of smectite's shrink/swell potential [27]. This characteristic of smectite clay may help explain the distinctly observable differences seen in trace soil patterns when dry or wet soil was transferred to fabric.

In summary, there was a strong trend for a greater quantity of soil objects, in particular soil aggregates, to be transferred to clothing fabric when these soils were wet (Table 3 and Figure 8). Soil aggregates made up approximately two-thirds of all soil objects detected by image processing. Dry soil produced the largest percentage of individual soil objects transferred per area of fabric; with wet soil producing a greater percentage of aggregates.

Discussion

These soil transference experiments (STEs) can only indicate potential soil transfer patterns when a clothed victim is dragged across soil. Other modes of soil transfer onto fabric, such as placing a clothed victim on soil [16], or trace soil patterns from a violently struggling victim, will produce their own unique sets of soil transfer patterns.

Of primary interest in these STEs was whether fabric type, irregularities in the structure of the fabric (such as seams) and appendages (buttons) could influence resulting soil transfer patterns. These latest experiments found that:

(i) fabric type did not show a consistent influence on transfer patterns and

(ii) appendages (buttons) and irregularities in fabric structure (seams) did influence the directionality of soil objects transferred and were important markers in determining the direction of drag.

Six of the ten patterns were seen in all 20 soil types: soil trails, soil accumulating in front and on top of raised seams, soil accumulating and delineating on crease marks and folds. Soil transfer patterns involving buttons were extremely consistent, with soil traces on buttons occurring in both wet and dry soil STEs on all soils tested. Buttons were 'dusted' with dry soil with 100% consistency and when using wet soil, buttons had clumps of soil on top or underneath the leading edge with 90% consistency. Elongate scratches on buttons occurred using 18 of the 20 soils tested.

The least consistent soil transfer patterns were random speckling of fabric with soil, damage to fabric and elongate organic soil particles aligned with direction of movement. A random speckle of soil on the fabric, which is a pattern consistently seen when weighted fabric is only placed on the soil [16], was noted in only 1.5% of fabric squares. The soil types this pattern appeared in were very dry and rich in light-weight organic particles, such as straw.

The other pattern not seen in all soils was minor damage to the fabric involving disruption of the fibre structure caused by forced contact with fragments of hard angular surface soil. Out of the four fabric types tested, this pattern only persisted when cotton fabric was dragged across very dry, clay-rich soil, with a hard massive structure. The length of time this minor fabric damage persisted was not documented in these STEs. It must be noted that movement over the soil surface only occurred for 3 seconds and the fabric was weighed down by a 2 kg weight.

The previously described method of comparing the quantity of individual and aggregate soil objects was chosen to illustrate the effect of different soil types on trace soil patterns. To ascertain whether fabric type had any consistent effect on the amount of soil transferred, image processing data recording the number of soiled pixels transferred in two STEs/ fabric type was collated and averaged (Figure 11 and Figure 12). It was hoped that comparing the quantity of soiled pixels of fabric would better enable any effect of four different fabric types on soil transference to be discovered.

When wet natural clay-rich soils from UTas farm (sites 1 to 3) were used, there was a clear trend for a distinctly greater quantity of pixels to record soiling; regardless of the fabric used. Site 1 is classified as a Brown Chromosol [23]; a duplex soil with non-restricted clayey subsoil (Table 1; (*i.e.,* water flow and roots have easy access into the subsoil)). Site 2 is a Brown Sodosol, a duplex soil with restricted sodic clayey subsoil (*i.e.,* water flow and roots have restricted access into the subsoil). Site 3 is a Brown Vertosol, a poorly-structured cracking clay. This trend was also identified at RTBG using natural loamy Brown Dermosol at site 9 and anthropogenic, organic-rich sandy loam soil from the rose garden bed (site 7). These results correspond with previous laboratory and field results [15,16,21]. Natural well-structured clayey Brown Kandosol with boulders from Mt Wellington (site 4) and Anthropogenic gravel-rich soil sites 5, 6 and 8 at RTBG did not show this trend. The reason why wet clay-rich soil from site 4 did not display the same distinct influence on trace soil patterns as other clay-rich soils tested from UTas Farm is not clear. The surface layer of this Brown Kandosol was water repellent and had a higher carbon content (12.8%) than soils from UTas farm (sites 1 to 3). All three horizons from site 4 had a sandy clay loam texture [28], which also differed from the predominantly clayey texture of soils from UTas farm.

Out of the four fabrics tested, nylon fabric tended to record the lowest-to-second-lowest quantity of soiled pixels when dragged across wet soil. Otherwise, no particular fabric type could be consistently identified as influencing the resulting trace soil pattern when soil was dry or wet.

Conclusions

Laboratory soil transference experiments (STEs) used the transfer method of dragging weighted clothing fabric across wet and dry soil from UTas farm, Mt Wellington and RTBG, to document trace soil patterns.

Three hundred and twenty (320) STEs were undertaken on anthropogenic and natural soils produced ten patterns identified by naked eye and confirmed by light microscopy and image processing. Out of the ten patterns identified, three involved buttons that had not been previously documented and another four patterns had only been documented in field experiments. Six patterns were identified in trace soil on the four different fabric types, using all 20 soils. However, there was no consistent trend identified that fabric type had influenced resulting trace soil patterns. Of greater impact to trace soil patterns was clothing seams, buttons, soil moisture and the mineralogical content of clay fractions (*i.e.* presence of smectite) in producing trace soil patterns. Abundance of soil transferred was dependant primarily on soil moisture, clay content, particle size and clay mineralogy (e.g. smectite). Dark organic loamy-sand textured soil provided the most easy to identify soil transfer patterns against the white fabric.

Image processing software proved valuable in providing quantifiable graphical presentations on:

(i) quantity of soil transferred, (ii) percentage of individual soil objects and aggregates transferred and (iii) direction patterns and (iv) the ability to identify and compare Munsell colours.

Future experiments will be required to test this new method of forensic soil analysis using an expanded range of clothing fabrics and other methods of soil transfer (e.g. in saturated subaqueous soils under water). At present, image processing software was only programmed to identify soil objects on a white homogenous fabric background. Trace soil patterns on clothing will differ depending on whether a victim is conscious or unconscious when their body makes contact with a soil surface. Developing a method to objectively and scientifically identify and interpret these trace soil patterns would be of substantial benefit to forensic investigators as to warrant further investigations.

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References

1. Fitzpatrick R, Raven M (2012) How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists. *Soil Horiz*53:14-29.
2. Fitzpatrick R, Raven M, Forrester S (2009) A systematic approach to soil forensics: criminal case studies involving transference from crime scene to forensic evidence. In: Ritz K, Dawson L, Miller D (eds.) Criminal and Environmental Soil Forensics. Netherlands: Springer p. 105-127.
3. Fitzpatrick R, Raven M (2013) Soils In: Siegel J, Saukko P (eds.) Encyclopedia of Forensic Sciences. second ed. Waltham, MA: Academic Press. p. 206-12.
4. Fitzpatrick R (2013) Soil: forensic analysis. In: Jamieson A, Moenssens A (eds.) Wiley Encyclopedia of Forensic Science. Chichester, West Sussex
5. Murray R (2011) Evidence from the Earth: Forensic Geology and Criminal Investigation. (2ndedn.) Missoula, MT: Mountain Press Publishing.
6. Pye K (2007) Geological and Soil Evidence: Forensic Applications. Boca Raton, FL: CRC Press.
7. Ruffell A, McKinley J (2008) Geoforensics. Chichester: John Wiley & Sons, Ltd.
8. Morgan R, Bull P (2007) Forensic geosciences and crime detection: Identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale*127:73-89.
9. Bull PA, Parker A, Morgan RM (2006) The forensic analysis of soils and sediment taken from the cast of a footprint. *Forensic Sci Int* 162: 6-12. [Crossref]
10. Fitzpatrick R, Raven M, Self P (2011) Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to operation Dargan. Centre for Australian

Forensic Soil Science Restricted Client Report. p. 1-116.

11. Raven M, Fitzpatrick R, Self P (2016) Trace evidence examination using laboratory and synchrotron X-ray diffraction techniques Paper no. 1131. 35th International Geological Congress, Symposium on Forensic Soil Science and Geology. Cape Town, South Aftrica.

12. Martin B (2012) The State of Western Australia v. Rayney. [No 3]: WASC 1-369.

13. Martin B (2012) Judgement Summary: The State of Western Australia v. Rayney. [No 3]: WASC; p. 1-13.

14. Morgan R, Cohen J, McGookin I, Murly-Gotto J, O'Connor R, Muress S, et al. (2009) The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Sci Justice* 49: 277-285. [Crossref]

15. Murray K, Fitzpatrick R, Bottrill R, Berry R, Kobus H (2016) Soil transference patterns on bras: Image processing and laboratory dragging experiments. *Forensic Sci Int* 258: 88-100. [Crossref]

16. Murray K, Fitzpatrick R, Bottrill R, Kobus H (2017) Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations. *Forensic Science Int*. [In press]

17. Sugita R, Marumo Y (1996) Validity of color examination for forensic soil identification. *Forensic Science Int* 83: 201-210.

18. Bigham J, Ciolkosz E (1993) Soil Color. SSSA Special Publication 31: 159.

19. Fitzpatrick R, Raven M (2016) Guidelines for conducting criminal and environmental soil forensic investigations: Version 10.1. South Australia: Centre for Australian Forensic Soil Science (CAFSS).

20. Munsell_Color_Company (2009) Munsell Soil Color, Book. Michigan: Munsell Color X-rite.

21. Murray K, Fitzpatrick R, Bottrill R, Berry R, Woolley R, Doyle R, et al. (2016) Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: laboratory dragging experiments. *Acid Sulfate Soils* Report No ASSC_096.

22. Adelaide: The University of Adelaide, Australia (2015) p. 1-100. (http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=34394;m=view).

23. Department of Primary Industries P, Water and Environment (2015) LISTmap - Land Information System Tasmania. Tasmania: DPIPWE; http://maps.thelist.tas.gov.au/listmap/app/list/map.

24. Isbell R, National_Committee_on_Soils_and_Terrain (2016) The Australian Soil Classification. 2nd ed. Clayton, Victoria, Australia: CSIRO Publishing.

25. IUSS_Working_Group_WRB. World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No 106. Rome: FAO p. 1-181. (http://www.fao.org/3/a-i3794e.pdf).

26. Fitzpatrick R (2013) Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use. In: Taha F, Abdelfattah M (eds.) Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources. Netherlands: Springer; p. 51-83.

27. Holcombe R (2011) GEOrient. Queensland, Australia: School of Earth Sciences, University of Queensland. http://www.holcombe.net.au/software/rodh_software_georient.htm.

28. Weaver C (1990) Clays, muds and shales. In: Weaver C (ed.) Developments in Sedimentology. Amsterdam: Elsevier.

29. McDonald R, Isbell R (2009) Soil Profile (3rdedn.) Melbourne: CSIRO Publishing.

5. CHAPTER 5 An investigation of the pattern formed by soil transfer when clothing fabrics are placed on soil using visual examination and image processing analysis

This chapter uses the same soil and fabric types as used in chapter 4, to compare the trace soil patterns resulting when a simulated human body is merely placed upon a soil surface. Trace soil patterns are documented to indicate whether some patterns are universal across all fabrics tested.

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Principal Author

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Contribution to the Paper	I wrote the initial and subsequent drafts. These were edited by Rob Fitzpatrick and Hilton Kobus. XRD analysis included in this paper was undertaken by Ralph Bottrill.		
Overall percentage (%)	90		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

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Name of Co-Author	Rob Fitzpatrick		
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Forensic Science and Criminology

Research Article

An investigation of the pattern formed by soil transfer when clothing fabrics are placed on soil using visual examination and image processing analysis

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Abstract

A series of soil transference experiments led to the development of two methods to identify and interpret trace soil patterns on clothing fabric. Instigated by an unsolved murder, this paper developed previous field experiments to visually interpret trace soil patterns on a simulated clothed victim placed on soil during a crime. Soil transfer patterns were easily identified using direct visual analysis. Image processing software was used to analyse digital photographs and provided objective, standardised and comprehensive numerical data. This object-oriented classification of all trace soil objects transferred (≥ 2 pixels) allowed directionality and abundance of transferred soil to be determined and additionally Munsell soil colour classification could be made.

To gain greater understanding of how the physical transference of soil on a victim's clothing might indicate the circumstances of an attack, 400 soil transfer experiments investigated two methods of placing weighted fabric on a wet or dry soil surface. The methodology has now been applied in other case work.

Introduction

Forensic soil evidence has the ability to help police solve crime by providing valuable associative physical evidence in any circumstance where it is found [1-9]. However, a void in forensic knowledge was discovered during a homicide investigation in Western Australia. During the trial in 2012, which was before a judge only, the judge concluded that the mineralogy data from the brick particles on the victim's bra and the bricks from her front driveway suggested she was initially attacked in her front yard and not where her body was buried [10-14].

However, at the time of the trial, no scientific research had been undertaken to interpret trace soil evidence patterns on common clothing fabric types. Therefore, the circumstances of the attack could not be ascertained from this soil evidence alone [12,14]. This murder remains unsolved.

Recent soil transfer experiments (STEs), both in the laboratory and field, documented distinct differences in trace soil patterns when a simulated clothed human body is either dragged or placed upon a soil surface [15-17]. Up to 20 different soil types and five common clothing fabrics were tested to better understand the influence of a specific soil transfer method, soil type, fabric type and surface irregularities/ appendages (clothing seams, plastic buttons and metal buckles) on resulting trace soil patterns on fabric. An important outcome of this work was the publication of results from testing different soil transference methods relevant to soil evidence on clothing (mainly from a bra) from the unsolved homicide from Western Australia [10-14].

Using the same 20 soil types and four fabrics (cotton, polyester-cotton, nylon and polar fleece (polyester brushed on both sides)), 400 STEs were conducted to advance scientific knowledge of forensic soil science.

Materials and methods

Soil samples

Twenty (20) natural and anthropogenic soils [18] (otherwise known as Technosol [19,20] or human-altered or human-transported (HAHT) [21]), originated from three locations: the University of Tasmania (UTas) Research Farm at Richmond Rd, Cambridge, Pinnacle Rd on Mount Wellington and the Royal Tasmanian Botanical Gardens (RTBG), Lower Domain Rd, Hobart, Tasmania, Australia (Figure 1) [22]. Table 1 provides a summary of the soil morphology and classifications of these soil samples. Full descriptions of each soil is provided in Murray et al. [22].

Experimental design

Placing experiments: The method devised by Murray et al. [15,16,22] to simulate a lifeless or incapacitated clothed human body dragged across a soil surface, was adapted to test two transfer methods mimicking the placement of a clothed body on a soil surface. A glass

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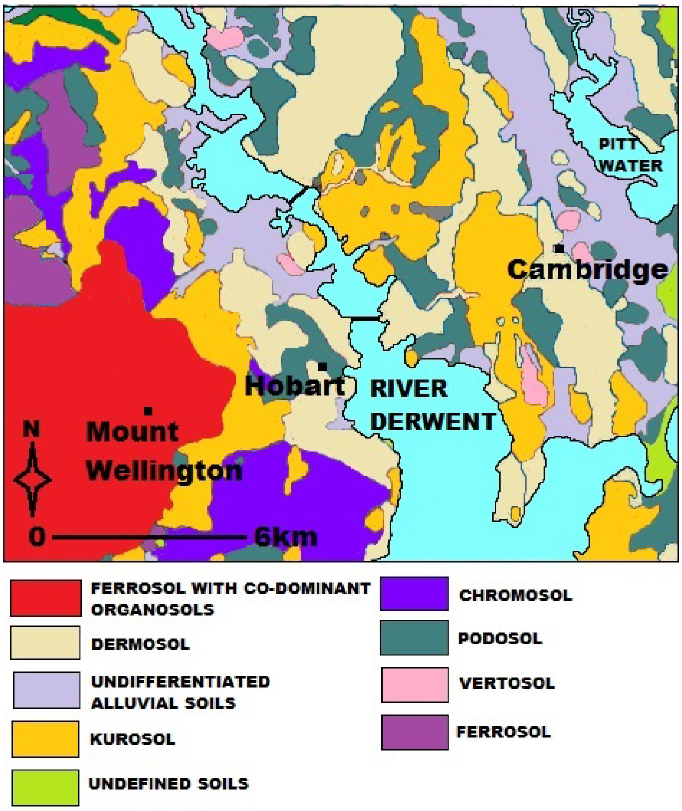


Figure 1. Soil map shows the three soil site areas of Cambridge, Hobart and Mount Wellington, Tasmania [23]; provided by Murray et al. [22].

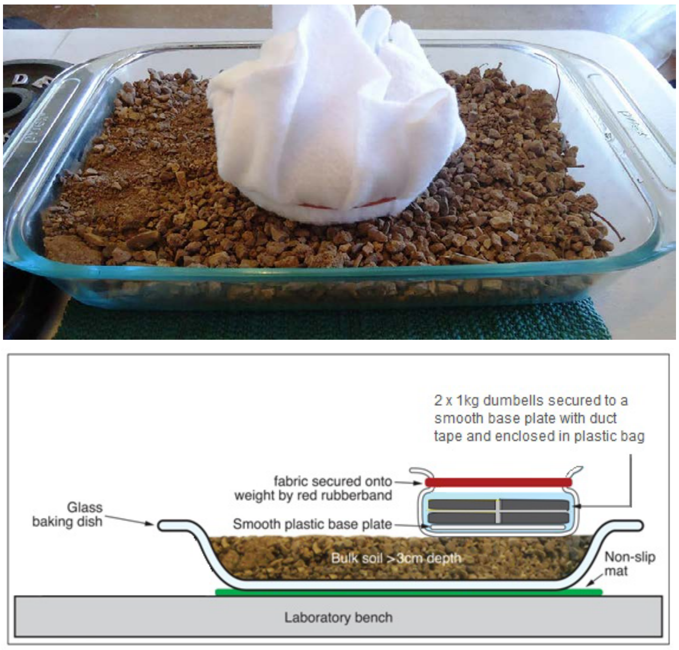


Figure 2. Photograph (above) and cross-section of a weighted fabric square placed on soil material using placement method 1, during a two minute count Soil Transference Experiment (STE). The glass dish containing bulk soil was placed on a nonslip mat to prevent movement during each STE.

Pyrex 3 qt/2.8 L dish was filled to >3 cm with bulk soil and placed on a non-slip mat. Experiments were conducted using both wet and dry soil. To mimic clothing seams, the 30 cm^2 fabric squares were sewn down the middle with a raised seam. Using the same method as Murray et al. [22], half of the cotton squares had a 1 cm diameter plastic button sewn onto them. White coloured fabric was chosen to enable easy detection of trace soil transferred in minute amounts.

Using placement method 1, a fabric square was secured to a 2 kg weight by a strong rubber-band. this simulated firm-fitting clothing worn by a human victim. In order to achieve reproducible and consistent results, the weighted fabric was placed on wet or dry soil in a glass baking dish and timed for 2 minutes (Figure 2). Great care was taken to minimise any movement of the fabric across the soil surface. The weighted fabric was then carefully lifted up and placed on a clean surface, in order to immediately photograph the soil transference pattern. The attached weight not only stabilised soil transfer patterns, but kept the surface to be photographed and photomicrographed flat during analysis.

Placement method 2 simulated a clothed body wearing loose-fitting clothing. Randomly folded non-weighted fabric was placed on a wet or dry soil surface (Figure 3). Immediately, the 2 kg weight was gently placed on top and the placement timed for 2 minutes. The weight would then carefully be lifted off and the fabric square gently lifted and spread flat and soil-side-up on a clean bench for photographing with a digital camera.

These digital photographs were then uploaded to a computer with image processing software which had been manually programmed to convert its default RGB colour system to the Munsell soil colour system preferred by forensic soil scientists in the field [25-27]. Full details regarding the use of image processing software to identify the Munsell soil colour of trace soil evidence is discussed in Murray et al. [15-17]. This research focused primarily on the visual interpretation of trace soil patterns on clothing to identify the circumstances befalling a victim during an attack.

Numerical data on each trace soil pattern provided a scientific and objective analysis of trace soil patterns that could be used to confirm patterns identified by human eye. Image software was also programmed to gather data on the quantity and directionality of soil objects transferred. Directionality was used to better understand the soil transfer method and was graphed using quick and easily compared rose diagrams with GEOrient version 9.5.0 [28]. Due to limitations in the manual programming of this software, soil objects <100 μm were disregarded from analysis [15-17,22].

Figure 3. Using placement method 2, loosely-folded fabric is first placed on a soil surface before a 2kg weight is placed on top and the 2 minute count commences.

Table 1. Soil morphology and Australian Soil Classification of soil materials [18] and approximate corresponding classifications for World Reference Base for Soil resources class [19] provided by Murray et al. [22].

Locality (depth cm)	**Centre for Australian Forensic Soil Science (CAFSS) code**	**Munsell[1] Soil Colour fine <2 mm (wet)** (dry)	**Soil type[2]**	**Brief description**	**The Australian soil classification**	**The world reference base for soil resources (WRB)**
Site 1: UTas farm horizon 1 (0-10 cm)	110.1.1	**Very dark brown 10YR 2/2** Dark grayish brown 10YR 4/2	Duplex soil with nonrestricted clayey subsoil	Gravel (50%); clayey sand, water repellent, 6.92% Carbon (C).	Humose, Mesotrophic, Brown Chromosol; medium, moderately gravelly, loamy, clayey, moderate	Haplic, Luvisol (Clayic, Cutanic)
Site 1: UTas farm horizon 2 (15-30 cm)	110.1.2	**Very dark brown 10YR 2/2** Brown 10YR 5/3	As above	Gravel (45%); sandy loam, water repellent, 2.46% Carbon (C).	As above	As above
Site 1: UTas farm horizon 3 (40-60 cm)	110.1.3	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	As above	Gravel (90%); heavy clay, non-water repellent, 0.92% Carbon (C).	As above	As above
Site 1: UTas farm horizon 4 (60-80 cm)	110.1.4	**Strong brown 7.5YR 5/6** Reddish yellow 7.5YR 6/6	As above	Gravel (90%); medium-heavy clay, non-water repellent, 0.26% Carbon (C).	As above	As above
Site 1: UTas farm horizon 5 (80-100 cm)	110.1.5	**Dark brown 7.5YR 3/4** Reddish yellow 7.5YR 6/6	As above	Gravel (40%); clayey sand, non-water repellent, 0.19% Carbon (C).	As above	As above
Site 2: UTas farm horizon 1 (0-17 cm)	110.2.1	**Very dark brown 10YR 2/2** Grayish brown 10YR 5/2	Duplex soil with restricted sodic clayey subsoil	Gravel (35%); sandy loam, non-water repellent, 2.61% Carbon (C).	Vertic, Mottled-Mesonatric, Brown Sodosol; medium, moderately gravelly, loamy, clayey, deep	Vertic, Abruptic Solonetz (Albic, Hypernatric)
Site 2: UTas farm horizon 2 (17-34 cm)	110.2.2	**Brown 10YR 4/3** Pale brown 10YR 6/3	As above	Gravel (95%); medium-heavy clay, non-water repellent, 1.14% Carbon (C).	As above	As above
Site 3: UTas farm horizon 1 (0-10 cm)	110.3.1	**Very dark gray 10YR 3/1** Dark grayish brown 10YR 4/2	Poorly structured cracking clay	Gravel (90%); medium clay, water repellent, 2.37% Carbon (C).	Endocalcareous, Massive, Brown Vertosol; very gravelly, fine, very fine, deep	Calsic, Vertisol (Gilgaic, Gleyic)
Site 3: UTas farm horizon 2 (20-40 cm)	110.3.2	**Yellowish brown 10YR 5/4** Grayish brown 10YR 4/2	As above	Gravel (97%); heavy clay, non-water repellent, 0.84% Carbon (C).	As above	As above
Site 3: UTas farm horizon 3 (40-70 cm)	110.3.3	**Light yellowish brown 10YR 6/4** Light gray 10YR 7/2	As above	Gravel (90%); medium clay, non-water repellent, 3.54% Carbon (C).	As above	As above
Site 3: UTas farm horizon 4 (70-110 cm)	110.3.4	**Yellowish brown 10YR 5/4** Brown 10YR 5/3	As above	Gravel (90%); heavy clay, non-water repellent, 0.44% Carbon (C).	As above	As above
Site 4: Mount Wellington horizon 1 (0-10 cm)	110.4.1	**Very dark brown 10YR 2/2** Very dark grayish brown 10YR 3/2	Well structured clayey soil with boulders	Gravel (70%); sandy clay loam, water repellent, 12.8% Carbon (C).	Humose-Mottled, Placic, Brown Kandosol; medium, moderately gravelly, loamy, clayey, deep	Xanthic, Ferretic, Ferralsol (Clayic, Colluvic)
Site 4: Mount Wellington horizon 3 (40-60 cm)	110.4.3	**Strong brown 7.5YR 4/6** Brownish yellow 10YR 6/6	As above	Gravel (70%); sandy clay loam, non-water repellent, 0.96% Carbon (C).	As above	As above
Site 4: Mount Wellington horizon 5 (110-140 cm)	110.4.5	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	As above	Gravel (75%); sandy clay loam, non-water repellent, 0.34% Carbon (C).	As above	As above
Site 5: rose garden path (0-10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	Anthropogenic gravelly sandy loam soil	Gravel (90%; arkosic sandstone and andesitic-to-weathered mafic igneous rock) loamy sand, water repellent, 0.7% Carbon (C).	Spolic anthroposol, very gravelly, sandy, very shallow	[3]Spolic technosol (Densic)
Site 6: brick fragments (0-2 cm)	110.6.2	**Red 2.5YR 5/8** Light red 2.5YR 7/8	Anthropogenic brick fragment-rich soil	Gravel (90%), sandy, water repellent, weathered brick fragments (0.5-4 cm), 1.2% C.	Urbic anthroposol, very gravelly, sandy, very shallow	[3]Urbic Ekranic technosol (Transportic)
Site 7: rose garden bed (0-10 cm)	110.7.1	**Black 10YR 2/1** Black 7.5YR 2.5/1	Anthropogenic, organic-rich sandy loam soil	Gravel (15% coarse river sand), loamy sand (25%), water repellent, 30% fine compost, 30% composted pine bark, 14% C.	Hortic anthroposol non-gravelly, sandy, shallow	[4]Hortic anthrosol (Escalic)
Site 8: Japanese garden bed (0-10 cm)	110.8.1	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	Anthropogenic, quartz-rich, gravelly, sandy soil	Gravel (90%: ~80% rounded quartz, 10% sub-rounded to angular dolerite;5% ironstone), loamy sand, water repellent, 3% C.	Spolic anthroposol, very gravelly, sandy, very shallow	[3]Spolic technosol (Grossartefactic, Transportic)

Site 9: south eastern boundary horizon 1 (5-0 cm)	110.9.1	Leaves not analysed for Munsell soil colour by naked eye	Natural organic-rich soil	Undecomposed Leaves (60%) and decomposed (40%)	Humose, mesotrophic, Brown Dermosol, non-gravelly, sandy, deep	Eutric Cambisol (Humic)
Site 9: south eastern boundary horizon 2 (0-10 cm)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	Natural loamy soil	Gravel (2%), loamy sand, water repellent, 23% C.	As above	As above

Where:

[1]Munsell soil colour [29]: measured on the fine earth fraction (<2 mm).

[2]Special-purpose technical soil classification system [24], which uses plain English and places strong emphasis on being either an anthropogenic soil or natural soil, the soil texture (e.g. gravelly, sandy, sandy loam) and the presence of high quantities of organic carbon (>10%; organic-rich).

[3]Classification of technosols [19]: Connotation: soils dominated or strongly influenced by human-made material; from Greek technikos, skilfully made. They contain a significant amount of artefacts.

[4]Classification of Anthroposol [19]: Connotation: soils with prominent characteristics that result from human activities; from Greek anthropos, human being (e.g. such as addition of organic material and cultivation).

[5]Classification of natural soils: Connotation: soils with substantial soil formation such as Dermosols [18] or Cambisols [19].

Table 2. Trace soil patterns identified on fabric using 'placing' as the transfer method.

	Soil transfer pattern	Symbol used	Figure	Location on fabric	Contributing soil characteristic
1	Speckling of soil on fabric	red circle	Figure 4 Figure 5 Figure 8	sporadically where fabric had made contact with soil surface	Marginally greater quantity of wet soil objects transferred (96% consistency) than dry (90%)
2	Fold and crease marks on draped cloth (Method 2)	green circle	Figure 4 Figure 5	delineating folds or creases on loosely draped cloth	100% consistency in all soils both dry and wet
3	Soiled water stains	blue circle	Figure 5 Figure 6	sporadically where fabric had made contact with soil surface	wet soil (45% consistency)
4	'Dusted' plastic buttons	orange circle	Figure 7	buttons sewn onto cotton fabric (no other fabrics had buttons)	very dry soil (55% consistency)
5	Muddy clumps on wet shiny plastic buttons	yellow circle	Figure 7	buttons sewn onto cotton fabric	wet soil (30% consistency)
6	Minimal amount of soil accumulated on raised surfaces	_	Figure 6	raised middle seams	Marginally greater quantity of wet soil objects transferred (19% consistency) than dry (6%)

Results and discussion

Trace soil patterns recorded on fabric using the soil transfer method of 'placing'

When a weighted fabric square was simply placed on soil, six transfer patterns were routinely identified using all soils tested (Table 2 and Figures 4-7). As hypothesised, previously documented soil transfer patterns that occurred when weighted fabric was dragged across a soil surface, were not seen in any of these soil transfer experiments [15-17,22]. The soil patterns not seen included soil 'trails' and elongated soil particles either embedded in fabric or aligned parallel with the direction of movement. Also missing was an accumulation of soil in front of buttons and raised seams, damage to fabric and scratches on buttons.

Trace soil patterns transferred to fabric depended primarily on soil moisture content, soil mineralogy (e.g. smectite) and clay fraction (<2 um) content. Wet soil tended to transfer a higher abundance of trace soil particles to fabric than when soil was dry. There was one exception to this, soils with a sandy clay loam texture, which is discussed in greater detail in section 3.5 below. Clothing fabric type had no observable effect on resulting trace soil patterns.

Directionality

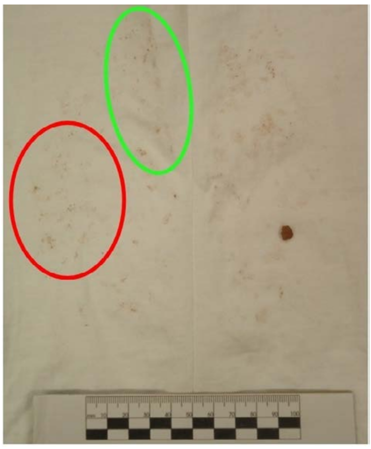
Using directional numerical data provided by image processing software, rose diagrams illustrated the directionality of wet and dry soil particles (≥2 pixels diameter) transferred onto clothing fabric (Figure 9). This methodology provided objective support to visual observations.

By mapping the directionality of thousands of soil particles down to 100 µm diameter, rose diagrams consistently created a simple yet definitive pictorial record of soil transferred onto fabric during placing experiments. Each Rose diagram only took minutes to create.

In each of the soils tested in placing STEs, there was no obvious movement of soil seen across the fabric; as witnessed in dragging STEs from soil 'trails' [15-17,22]. Minimal to negligible soil was transferred to the weighted fabric; compared to the transfer method of dragging. This resulted in several instances when there was insufficient data to create a rose diagram or the directional data for a particular STE was so limited, it affected the rose diagram's value. When dry soil was used, dry soil particles tended to remain as individual soil objects and not clump into aggregates. This lack of soil clumping or directional soil movement also helps explain the scattered random patterns depicted in each rose diagram.

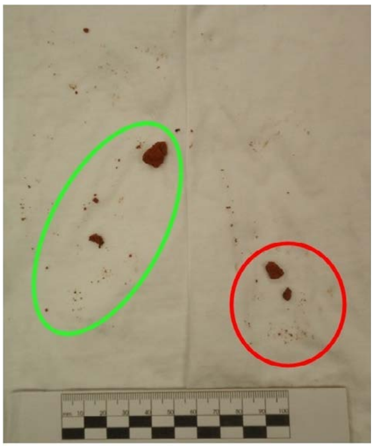
Dry hard soils, such as soils with massive structures found at UTas Farm, produced minimal soil transference patterns in placing experiments. This was also the case in the dry gravel-rich soil of the RTBG site 8 Japanese garden composed of 90% white gravel. Natural soil site 9 surface horizon 1 of undecomposed leaves, with negligible mineral soil content, transferred minimal trace soil to fabric.

Rose diagrams recorded random and scattered trace soil patterns with no obvious directionality that was seen when the same four types of fabric squares were dragged across a wet or dry soil surface [22]. The strong directionality identified by image processing software from dragging experiments was consistently seen throughout all twenty soils; regardless of fabric used or each soil type's differing mineralogy, grain size or amount of fine clay-sized soil particles. These initial experiments suggest that rose diagrams using image processing directional data



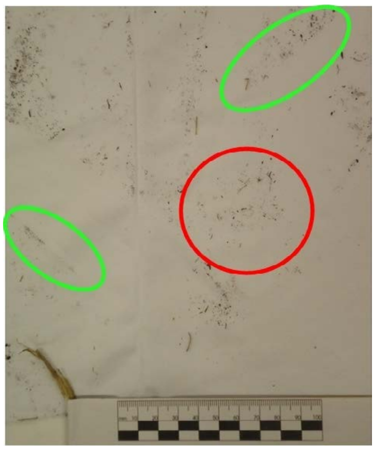
(A)DRY Site 6 brick fragments RTBG (cotton)

Figure 4(A). Trace soil patterns resulting from transfer method 2 that involved placing loosely draped weighted fabric for 2 minutes on a soil bed containing dry soil. Fabric tested: cotton. The difference soil moisture can make on resulting trace soil patterns is demonstrated by comparing the same fabric type placed on the same soil type; with the only difference being soil moisture content.



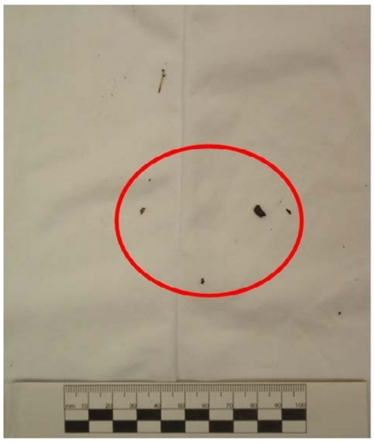
(B) WET Site 6 brick fragments (cotton)

Figure 4(B). Trace soil patterns resulting from transfer method 2 that involved placing loosely draped weighted fabric for 2 minutes on a soil bed containing wet soil. Fabric tested: cotton.



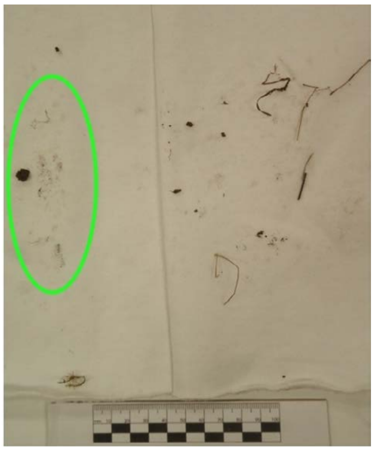
(C) DRY Site 7 rose garden bed RTBG (nylon)

Figure 4(C). Trace soil patterns resulting from transfer method 2 that involved placing loosely draped weighted fabric for 2 minutes on a soil bed containing dry soil. Fabric tested: nylon.



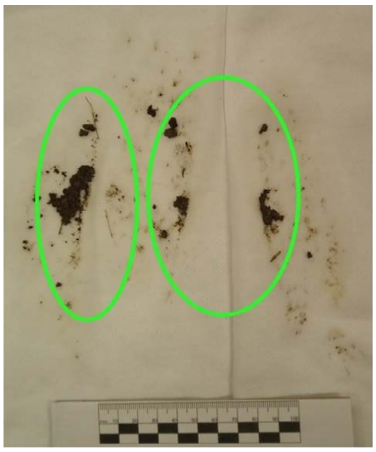
(D) WET Site 7 rose garden bed (nylon)

Figure 4(D). Trace soil patterns resulting from transfer method 2 that involved placing loosely draped weighted fabric for 2 minutes on a soil bed containing wet soil. Fabric tested: nylon.



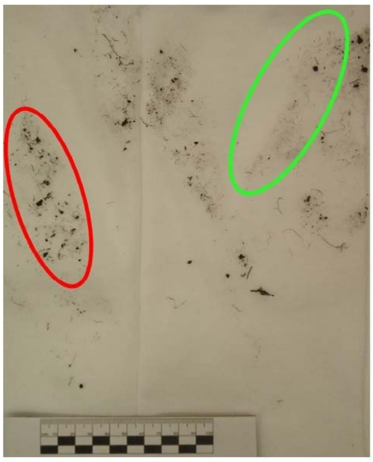
(A) DRY Site 1 surface horizon UTAS (Poly-cotton)

Figure 5(A). Trace soil patterns using transfer method 2, when loosely draped weighted fabric is placed for 2 minutes on a soil bed containing dry soil. Fabric tested: polyester-cotton. When comparing Figures 5(A to D), soil moisture content appears to make a greater difference to resulting trace soil patterns than fabrics tested.



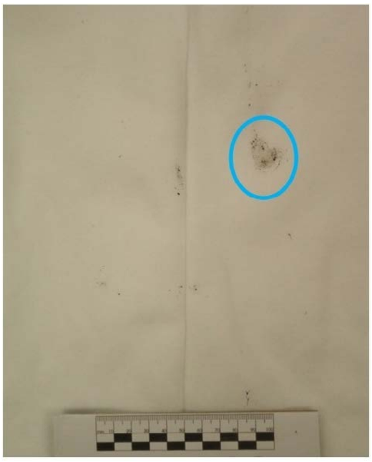
(B) WET Site 1 surface horizon (Poly-cotton)

Figure 5(B). Trace soil patterns using transfer method 2, when loosely draped weighted fabric is placed for 2 minutes on a soil bed containing wet soil. Fabric tested: polyester-cotton.



(C) DRY Site 4 horizon 1 Mt. Wellington (polar fleece)

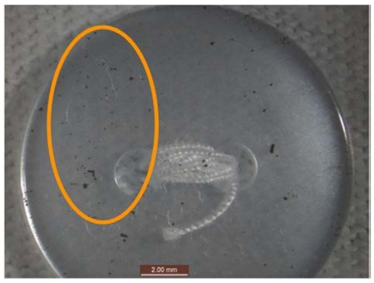
Figure 5(C). Trace soil patterns using transfer method 2, when loosely draped weighted fabric is placed for 2 minutes on a soil bed containing dry soil. Fabric tested: polar fleece (polyester brushed both sides).



(D) WET Site 4 horizon 1 Mt. Wellington (polar fleece)

Figure 5(D). Trace soil patterns using transfer method 2, when loosely draped weighted fabric is placed for 2 minutes on a soil bed containing wet soil. Fabric tested: polar fleece (polyester brushed both sides).

Figure 6. Wet trace soil from Site 2 horizon 1 UTas farm semi-dissolves and embeds in fabric fibres (cotton).



(A) DRY site 9 horizon 1 leaves, RTBG (cotton)

Figure 7(A). Photomicrograph of plastic button sewn onto cotton fabric and placed on dry soil. Button is 1cm diameter. Orange circle = very fine clay-sized particles ‘dusted’ sporadically over button.

(B) DRY site 7 rose garden bed, RTBG (cotton)

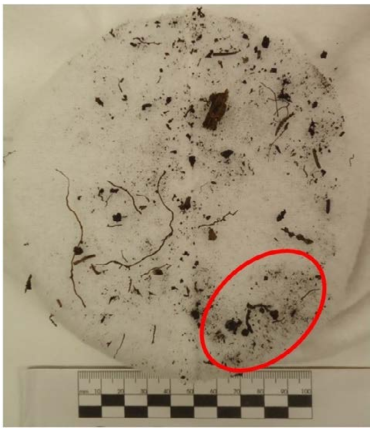
Figure 7(B). Photomicrograph of plastic button sewn onto cotton fabric and placed on dry soil. Buttons 1cm diameter. Orange circle = very fine clay-sized particles ‘dusted’ sporadically over button.

(C) WET site 7 rose garden bed (cotton)

Figure 7(C). Photomicrograph of plastic button sewn onto cotton fabric and placed on wet soil. Button 1cm diameter. Yellow circle = wet clumps of soil particles persisting to button.

D) WET site 9 horizon 2 mineral soil (cotton)

Figure 7(D). Photomicrographs of plastic buttons sewn onto cotton fabric and placed on wet soil. Buttons 1cm diameter. Yellow circle = wet clumps of soil particles persisting to button.



(A)DRY site 9 horizon 2 mineral soil, RTBG (polar fleece)

Figure 8(A). Polar fleece fabric speckled with soil in a dry placement on site 9 natural mineral soil, RTBG. In Figures 8 (A to B), soil moisture content had a more consistent influence on resulting trace soil patterns than did the four common fabrics tested. Red circle = a patch of fabric randomly specked by soil.

(B) WET site 9 horizon 2 mineral soil (polar fleece)

Figure 8(B). Polar fleece fabric speckled with clumps of soil in a wet placement on site 9 natural mineral soil, RTBG.

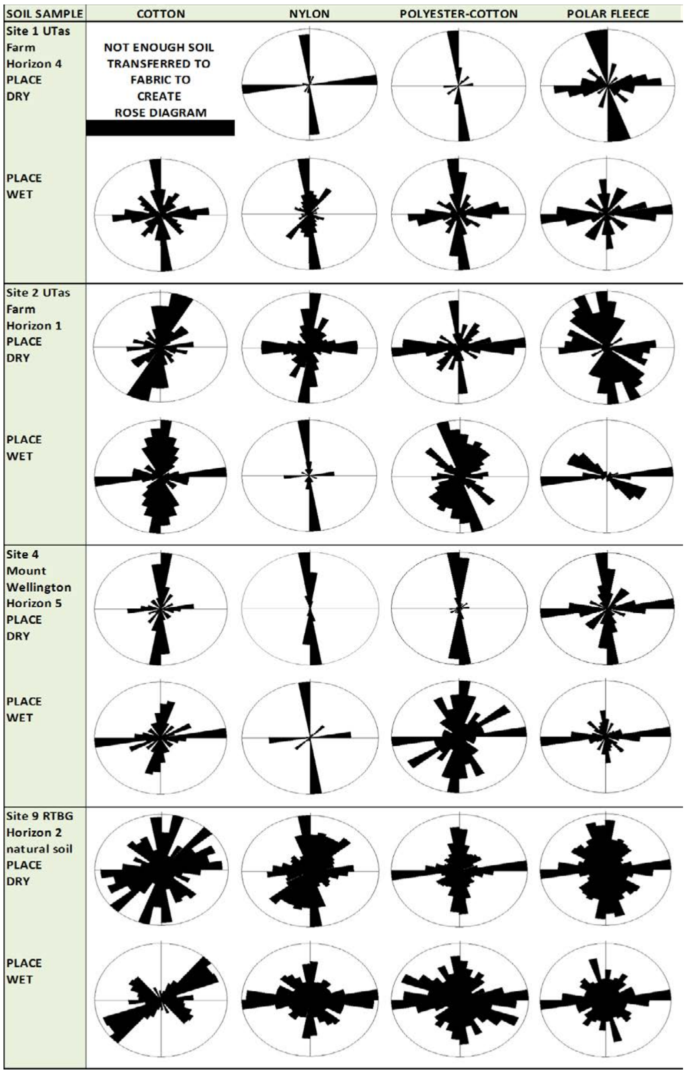


Figure 9. Rose diagrams display the directionality of wet and dry soil objects transferred onto fabric during STEs using soil from UTas Farm Site 1 horizon 4 and site 2 surface horizon, Mt. Wellington site 4 horizon 5 and RTBG site 9 mineral rich soil. A scattered and random pattern, lacking strong directionality, was produced when four fabric types were placed on a soil surface.

can indicate whether trace soil objects were transferred to fabric by placing or dragging a simulated clothed human body on a soil surface; regardless of the four fabric types tested.

Quantity of soil objects transferred to clothing fabric and analysed by soil type

A standardised objectivity of soil pattern analysis was achieved using quantitative graphical presentation of computer analysis of the number of digital pixels, containing either individual or aggregate soil objects (Table 3 and Figure 10). The level of precision attained when analysing trace soil patterns on clothing fabric had not previously been possible via traditional identification by naked eye alone

Soils were first grouped by location and then sub-grouped by soil moisture content. Numerical data was combined and averaged to produce graphs of aggregate and individual soil objects, transferred by one of two transfer methods of placing, from each soil sample to clothing fabric.

Soil objects covering > 0.5 million pixels were categorised as a low quantity of soil objects transferred to fabric. Soil objects covering 0.5 million to >1 million pixels were categorised within a moderate quantity of soil objects transferred. Soil objects covering 1 million pixels or higher were categorised as a high quantity of soil objects transferred [15-17,22].

Image processing numerical data enabled a thorough, detailed and objective interpretation of the relationships between soil types, clay minerals (smectite) and soil moisture content.

Compared to the quantity of soil objects transferred by the transfer method of dragging the same fabric types across the same 20 soils [22], the quantity of soil transferred by placing was in most cases so low as to indicate only that increased soil moisture tended to increase the quantity of soil objects transferred (Figure 11). This was the general trend across all soils tested, regardless of soil mineralogy (e.g. smectite) and clay content. The exception to this was soil with a sandy clay loam texture; namely natural soils from site 4: Mt. Wellington and Anthroposol site 5: rose garden path (Figure 10). Although site 5 was 90% gravel, the soil matrix had a sandy loam texture.

Table 3. Summary of soil data documented using naked eye, XRD and NDIR analysis and image processing of the 20 soil types and trace soil objects transferred to clothing fabric; as provided by Murray et al. [22].

Locality	**Centre for Australian Forensic Soil Science (CAFSS)**	**Munsell[1] soil colour <2 mm fraction**	**Dominant trace soil[2] Munsell colour**	**Ave. soil transferred (individual + aggregates) in pixels[3]**		**Weight % Clay content (Smectite)**	**% Organic content**	**% Gravel content**
(Depth cm)	**code**	**(wet)** (dry)	**(wet)** (dry)	**(wet)** (dry) **High quantity** **Moderate** **Low**	**(H)** **(M)** **(L)**			
Site 1: UTas farm horizon 1 (0-10 cm)	110.1.1	**Very dark brown 10YR 2/2** Dark grayish brown 10YR 4/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**34026** 45481	**(L)** (L)	5 ± 1	6.92	50
Site 1 horizon 2 (15-30 cm)	110.1.2	**Very dark brown 10YR 2/2** Brown 10YR 5/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**20415** 14212	**(L)** (L)	13 ± 2	2.46	45
Site 1 horizon 3 (40-60 cm)	110.1.3	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**75087** 3017	**(L)** (L)	56 ± 5	0.92	90
Site 1 horizon 4 (60-80 cm)	110.1.4	**Strong brown 7.5YR 5/6** Reddish yellow 7.5YR 6/6	**Light gray 7.5YR 7/2** Light gray 10YR 7/2	**16783** 4820	**(L)** (L)	59 ± 5	0.26	90
Site 1 horizon 5 (80-100 cm)	110.1.5	**Dark brown 7.5YR 3/4** Reddish yellow 7.5YR 6/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**22959** 8537	**(L)** (L)	52 ± 5	0.19	40
Site 2: UTas farm horizon 1 (0-17 cm)	110.2.1	**Very dark brown 10YR 2/2** Grayish brown 10YR 5/2	**Very dark brown 7.5YR 2.5/2** Llight gray 10YR 7/2	**17521** 20775	**(L)** (L)	3 ± 1	2.61	35
Site 2 horizon 2 (10-34 cm)	110.2.2	**Brown 10YR 4/3** Pale brown 10YR 6/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**63408** 814	**(L)** (L)	5 ± 2	1.14	95
Site 3: UTas farm horizon 1 (0-10 cm)	110.3.1	**Very dark gray 10YR 3/1** Dark grayish brown 10YR 4/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**57457** 2638	**(L)** (L)	41 ± 4	2.37	90
Site 3 horizon 2 (20-40 cm)	110.3.2	**Yellowish brown 10YR 5/4** Grayish brown 10YR 5/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**21938** 382	**(L)** (L)	58 ± 5	0.84	97
Site 3 horizon 3 (40-70 cm)	110.3.3	**Light yellowish brown 10YR 6/4** Light gray 10YR 7/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**24092** 864	**(L)** (L)	46 ± 4	3.54	90
Site 3 horizon 4 (70-110 cm)	110.3.4	**Yellowish brown 10YR 5/4** Brown 10YR 5/3	**Light gray 10YR 7/2** Light gray 10YR 7/2	**28819** 1049	**(L)** (L)	64 ± 5	0.44	90
Site 4: Mount Wellington horizon 1 (0-10 cm)	110.4.1	**Very dark brown 10YR 2/2** Very dark grayish brown 10YR 3/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**30119** 60244	**(L)** (L)	7 ± 2	12.8	70
Site 4 horizon 3 (40-60 cm)	110.4.3	**Strong brown 7.5YR 4/6** Brownish yellow 10YR 6/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**7571** 139787	**(L)** (L)	10 ± 2	0.96	70
Site 4 horizon 5 (110-140 cm)	110.4.5	**Strong brown 7.5YR 4/6** Strong brown 7.5YR 5/6	**Light gray 10YR 7/2** Light gray 10YR 7/2	**26423** 35937	**(L)** (L)	5 ± 2	0.34	75
Site 5: RTBG rose garden path (0-10 cm)	110.5.1	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	**Light gray 10YR 7/2** Light gray 10YR 7/2	**22671** 49842	**(L)** (L)	19 ± 3	0.70	90

Site 6: RTBG brick fragments (0-2 cm)	110.6.2	**Red 2.5YR 5/8** Light red 2.5YR 7/8	**Very dark brown 7.5YR 2.5/2** Light gray 10YR 7/2	**100127** 69957	**(L)** (L)	Trace of Mullite	0.29	90
Site 7: RTBG rose garden bed (0-10 cm)	110.7.1	**Black 10YR 2/1** Black 7.5YR 2.5/1	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**1575421** 304925	**(H)** (L)	2 ± 1	14.0	15
Site 8: RTBG Japanese garden bed (0-10 cm)	110.8.1	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**11690** 4643	**(L)** (L)	2 ± 1	3.10	90
Site 9: RTBG SE boundary horizon 1 (5-0 cm above surface)	110.9.1	**Leaves** leaves	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**25563** 16127	**(L)** (L)	No XRD analysis	No NDIR analysis	Leaves
Site 9 horizon 2 (0-10 cm)	110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	**Very dark brown 7.5YR 2.5/2** Very dark brown 7.5YR 2.5/2	**1565993** 160684	**(H)** (L)	20 ± 3	22.8	2

Where: [1]Munsell Soil Colour [21]: measured by naked eye on the fine earth fraction (<2 mm).
[2]Munsell Soil Colour measured by image processing software from two digital photographs of trace soil on fabric.
[3]Average of two STEs tested using either wet or dry soil sample.
[4]XRD analysis of % weight clay (Smectite) content in homogenous bulk soil sample.
[5]NDIR analysis of organic content of homogenous bulk soil sample.
[6]Estimate by naked eye alone using method of McDonald and Isbell [30].

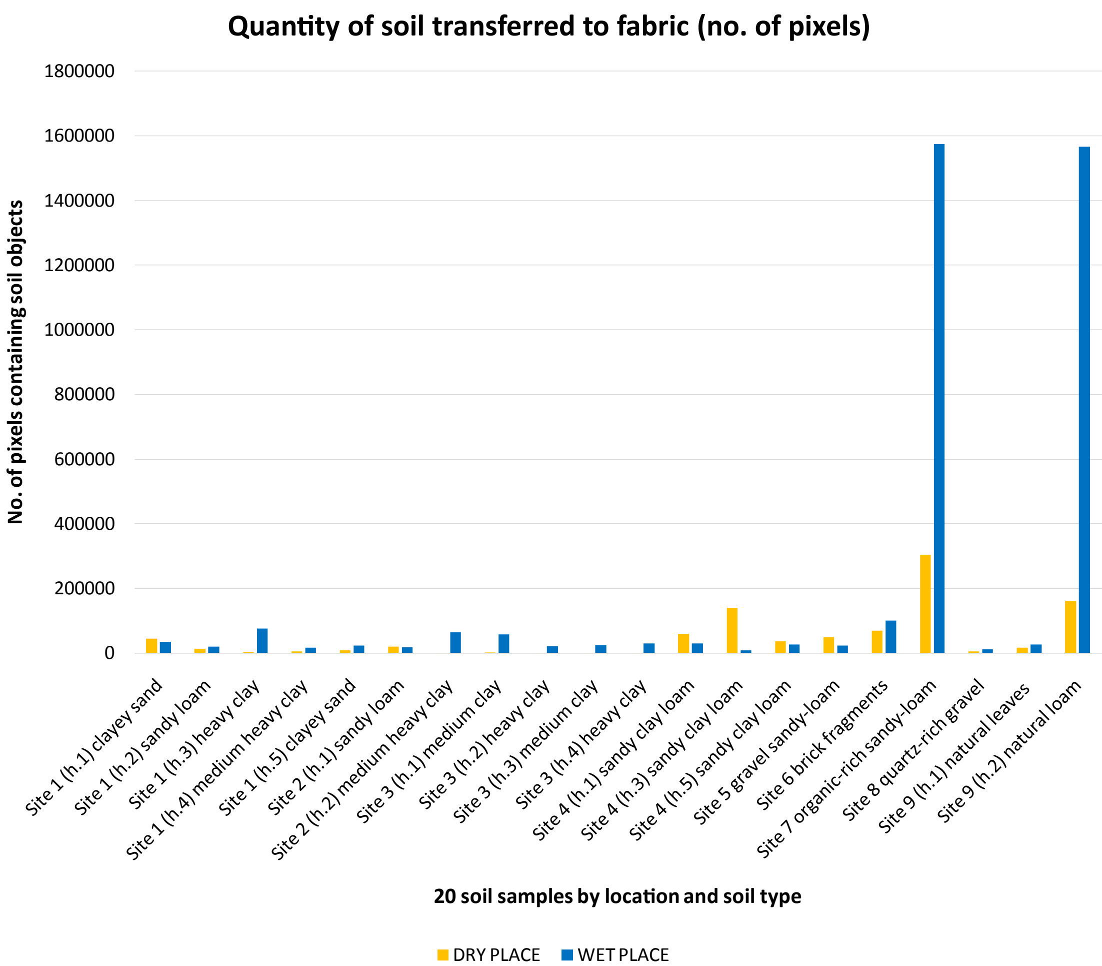


Figure 10. Quantity of soil transferred to fabric by placing weighted fabric on a soil surface; analysed by the total number of pixels in digital photographs that contained aggregate or individual soil objects. Image processing numerical data was subdivided first by location and then by soil moisture content [15,16].

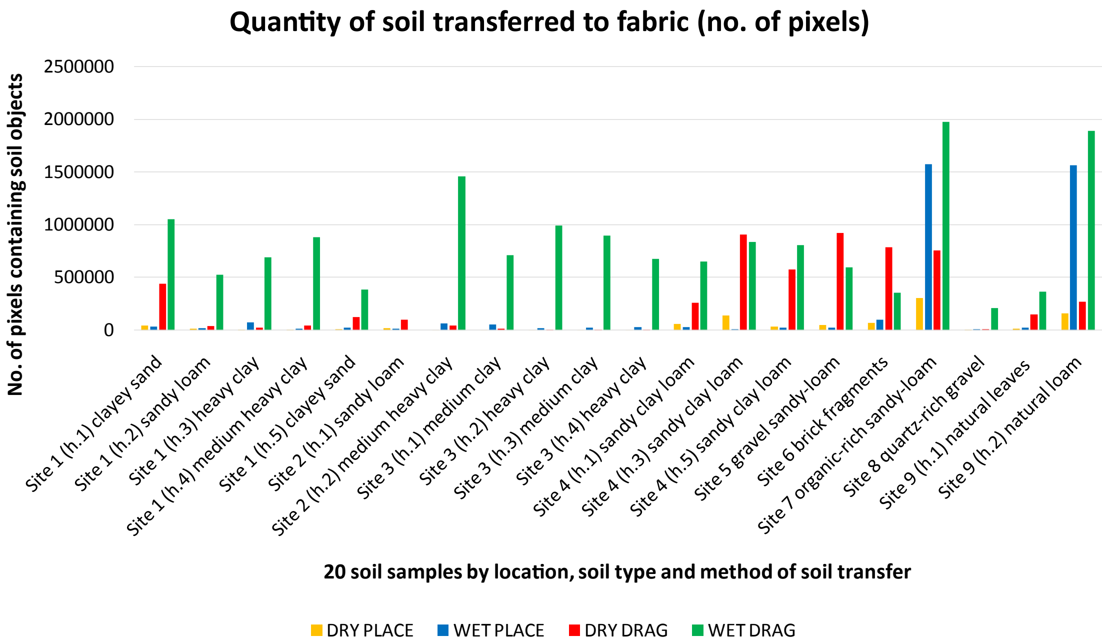


Figure 11. Comparison of quantity of soil transferred to fabric using the soil transfer methods of placing and dragging weighted fabric across a soil surface. Quantity of trace soil transferred was analysed by number of pixels in digital photographs that contained individual or aggregate soil objects. Image processing numerical data was subdivided by location and soil moisture content [22].

Conclusions

In a controlled laboratory environment, 400 soil transference experiments (STEs) produced six transference patterns identified by naked eye and confirmed by simple light microscopy and image processing. The minimal quantities of trace soil transferred from only placing a simulated clothed body on a soil surface made it more difficult to discover a relationship between soil moisture, particle size, mineralogy and soil objects transferred. Dark organic loamy-sand textured soil transfer patterns enabled easiest recognition by naked eye against the white fabric. However, image processing was equally capable of recognising all soil objects, regardless of Munsell soil colour. With further software development, image processing could be programmed to identify trace soil objects on underlying fabrics of differing colours, patterns and textile weaves.

Image processing provided objective support to visual observations by showing:

(i) how the quantity of soil objects transferred is influenced by soil mineralogy and moisture content,

(ii) percentage of aggregate and individual soil objects transferred,

(iii) lack on soil object directionality when 'placing' is the soil transfer method,

(iv) the unique ranges of Munsell soil colours of trace soil on fabric and

(v) the negligible influence the four fabric types tested had on trace soil patterns produced.

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References

1. Fitzpatrick R, Raven M (2012) How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists. *Soil Horiz* 53: 14-29.
2. Fitzpatrick R, Raven M, Forrester S (2009) A systematic approach to soil forensics: criminal case studies involving transference from crime scene to forensic evidence. In: Ritz K, Dawson L, Miller D, editors. Criminal and Environmental Soil Forensics. Netherlands: Springer Netherlands p. 105-127.
3. Fitzpatrick R, Raven M (2013) Soils. In: Siegel J, Saukko P (eds.) Encyclopedia of Forensic Sciences. 2nded. Waltham, MA: Academic Press p. 206-212.
4. Fitzpatrick R (2013) Soil: forensic analysis. In: Jamieson A, Moenssens A (eds.) Wiley Encyclopedia of Forensic Science. Chichester, West Sussex.
5. Murray R (2011) Evidence from the Earth: Forensic Geology and Criminal Investigation. 2ndedn. Missoula, MT: Mountain Press Publishing.

6. Pye K (2007) Geological and Soil Evidence: Forensic Applications. Boca Raton, FL: CRC Press.

7. Ruffell A, McKinley J (2008) Geoforensics. Chichester: John Wiley & Sons, Ltd.

8. Morgan R, Bull P (2007) Forensic geosciences and crime detection: Identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale* 127: 73-89.

9. Bull PA, Parker A, Morgan RM (2006) The forensic analysis of soils and sediment taken from the cast of a footprint. *Forensic Sci Int* 162: 6-12. [Crossref]

10. Martin B (2012) The State of Western Australia v. Rayney. [No 3]: WASC. p. 1-369.

11. Martin B (2012) Judgement Summary: The State of Western Australia v. Rayney. [No 3]: WASC. p. 1-13.

12. Fitzpatrick R, Raven M, Self P (2011) Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to operation Dargan. Centre for Australian Forensic Soil Science Restricted Client Report. p. 1-116.

13. Fitzpatrick R, Raven M (2012) The State of Western Australia v. Lloyd Patrick Rayney Trial: Request for Supplementary Statement Relating to Extraction of Particulate Material from Bra. Centre for Australian Forensic Soil Science. p. 1-17.

14. Raven M, Fitzpatrick R, Self P (2016) Trace evidence examination using laboratory and synchrotron X-ray diffraction techniques Paper no. 1131. 35th International Geological Congress, Symposium on Forensic Soil Science and Geology. Cape Town, South Aftrica.

15. Murray K, Fitzpatrick R, Bottrill R, Berry R, Kobus H (2016) Soil transference patterns on bras: Image processing and laboratory dragging experiments. *Forensic Sci Int* 258: 88-100.

16. Murray K, Fitzpatrick R, Bottrill R, Berry R, Woolley R, Doyle R, et al. (2015) Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: laboratory dragging experiments. Acid Sulfate Soils Report No ASSC_096 Adelaide: The University of Adelaide, Australia. p. 1-100.

17. Murray K, Fitzpatrick R, Bottrill R, Kobus H (2017) Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations: [In press]

18. Isbell R, National_Committee_on_Soils_and_Terrain (2016) The Australian Soil Classification. 2ndedn. Clayton, Victoria, Australia: CSIRO Publishing.

19. IUSS_Working_Group_WRB (2014) World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No 106. Rome: FAO. p. 1-181.

20. Soil_Survey_Staff (2014) Keys to Soil Taxonomy. 12thedn. Washington, DC: United States Department of Agriculture, Natural Resources Conservation Service.

21. Galbraith J (2012) Rationale for proposed changes to Soil Taxonomy concerning the International Committee for Anthropogenic Soils. *Soil Horizons* 2-6.

22. Murray K, Fitzpatrick R, Bottrill R, Kobus H (2016) Soil transference patterns on clothing fabrics and plastic buttons: image processing and laboratory dragging experiments. *Forensic Science and Criminology* 2(1): 1-12

23. Department of Primary Industries P, Water and Environment (2015) LISTmap - Land Information System Tasmania. Tasmania: DPIPWE. http://maps.thelist.tas.gov.au/listmap/app/list/map.

24. Fitzpatrick R (2013) Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use. In: Taha F, Abdelfattah M (eds.) Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources. Netherlands: Springer. p. 51-83.

25. Jantzi S, Almirall J (2011) Characterization and forensic analysis of soil samples using laser-induced breakdown spectroscopy (LIBS). *Anal Bioanal Chem* 400: 3341-3351. [Crossref]

26. Marumo Y (2003) Forensic examination of soil evidence. National Research Institute of Police Science 7: 95-111.

27. Sugita R, Marumo Y (1996) Validity of color examination for forensic soil identification. *Forensic Science Int* 83: 201-210.

28. Holcombe R (2011) GEOrient. Queensland, Australia: School of Earth Sciences, University of Queensland.

29. Munsell_Color_Company. Munsell Soil Color (2009) Book. Michigan: Munsell Color X-rite.

30. McDonald R, Isbell R (2009) Soil Profile. 3rdedn. Melbourne: CSIRO Publishing.

6. CHAPTER 6 General Discussion

This final chapter brings together a summary of the results and overall conclusions from the various laboratory and field soil transference experiments on clothing fabrics from the four published papers highlighted in chapters 2 to 5. The focus of these papers was to study, recognise and classify soil patterns transferred onto fabric when a clothed body is dragged or placed upon a soil surface. This was undertaken via traditional visual analysis by naked eye and image processing computer software. Image processing software was programmed to identify soil objects transferred to clothing fabric and their directionality; as well as the dominant range of Munsell colours of soil objects transferred from both wet and dry soil surfaces. Twenty different soil types and five common clothing fabrics were tested. Experiments were conducted in the laboratory; as well as at simulated crime scenes in the field. Overall, the research showed the following results:

- A range of reproducible trace soil patterns were produced when a body was placed or dragged across a soil surface.
- The deposition of soil on clothing fabric, along leading edges of protrusions such as buttons and seams, provided good directional indicators.
- Delicate soil traces on clothing could be easily lost if clothing was removed or packaged.
- Digital photographic recording of soil patterns could be used to evaluate the mode of transfer.
- Image processing software could be adapted to analyse the digital photographs and numerical data used to plot Rose diagrams of directionality information for soil drag and placement patterns.
- Image software could also determine Munsell colour classifications for soil deposits; providing useful comparative information with a source.
- The methodology used in this research could be applied to case-specific studies where experiments may be conducted at a suspect site.

In Chapter 2, Murray et al. (2016) published, as far as we are aware, the first soil transference experiments interpreting trace soil patterns on the surface of clothing fabric since Locard (1930). There are very few published works involving particle transference experiments on clothing and especially using bras (Morgan & Bull, 2007; Morgan, French, O'Donnell, & Bull, 2010). In the laboratory, a simulated clothed human body was dragged over seven (7) natural or anthroposol soil samples taken from different sites at Royal Tasmanian Botanical Gardens, Hobart, Tasmania. Trace soil patterns transferred onto nylon-elastane bra fabric were recorded using digital photographs and photomicrographs. Trace soil patterns were visually analysed by naked eye. Digital photographs of these patterns were objectively analysed using image processing software. A set of eight transfer patterns was identified with the quantity of soil transferred influenced primarily by the soil type, moisture content, particle size and mineralogy of the soil. Image processing was used to provide numerical data on the quantity of soil transferred, percentage of individual and aggregate soil objects, directionality and Munsell soil colour analysis of trace soil objects transferred onto bra fabric (Murray, Fitzpatrick, Bottrill, Berry, & Kobus, 2016).

In Chapter 3, Murray et al. (2017b) tested whether trace soil patterns identified from dragging experiments undertaken in the laboratory could also be identified at a simulated crime scene in the field. To create the most realistic conditions possible, a human rescue dummy dressed in a padded bra was dragged across two of the same soil locations where soil samples used in Murray et al. (2016) had originated. Not only were the same set of dragging transfer patterns identified, but additional patterns were added to the original set. Digital photographs taken 'in situ' of trace soil evidence on clothing at each simulated crime scene was then analysed visually and by image processing software. A soil transfer method of placing a clothed human body on different soil surfaces was also tested; resulting in a new set of transfer patterns. The consistency and reproducibility of results from this field research revealed the potential for the interpretation of trace soil patterns on clothing to shed light on the circumstances of an attack on a clothed human victim (Murray, Fitzpatrick, Bottrill, & Kobus, 2017b).

In Chapter 4, Murray et al. (2017c) tested the influence of four common fabric types (cotton, nylon, polyester- cotton and polar fleece (polyester brushed both sides) on soil transfer patterns resulting from a simulated clothed human body being dragged across wet and dry soil surfaces. The different types of soils tested was increased to twenty (20) different soil types. A plastic button was also sewn onto two cotton fabric squares per each soil type; with both wet and dry soil tested (Murray, Fitzpatrick, Bottrill, & Kobus, 2017c). With the inclusion of three new trace soil patterns due to the influence of buttons sewn on the fabric, the set of 'dragging' trace soil patterns was increased to ten different patterns.

In Chapter 5, Murray et al. (2017a) tested the transfer method of placing; using the same common fabric types and soil samples (Murray, Fitzpatrick, Bottrill, & Kobus, 2017a). These two papers were designed to explore whether underlying clothing fabric and accessories (buttons or clothing seams) have any influence over the resulting trace soil patterns. Researchers investigating the transfer of particulates other than soil onto clothing have sought to discover trends in their transference due to the underlying clothing textile (Bull, Morgan, et al., 2006; Lepot et al., 2015; Pounds & Smalldon, 1975a, 1975b, 1975c). Six soil transfer patterns were documented with varying consistency.

After conducting a substantial number of dragging and placing experiments using four common fabric types in these final papers, there was no evidence of any consistent relationship between soil transference patterns and underlying clothing textiles tested. This indicated that the type of fabric did not conclusively influence the resulting trace soil pattern. The mode of soil deposition, soil moisture and clay (smectite) content of the twenty soil types tested appeared to have a much greater influence on resulting trace soil patterns than any surface textures of the four common fabrics tested. However, the accessory seams and buttons provided evidence of the directionality of soil objects transferred when the transfer method was dragging. When the simulated clothed body was simply placed on soil, image processing analysis showed a non-directional and more tenuous (less persistent) transfer of soil objects onto clothing fabric. These results suggest that it may be valuable to police investigations for experimental studies to be undertaken on a wider range of soil types and locations; to document generalizable results. Another option may be to undertake experimental work on a case-by-case basis to offer evidence-based insights during police investigations (e.g. Fitzpatrick, 2015).

The potential for image processing software to be used in routine analysis of forensic soil evidence was tested in these papers. It took approximately a week to initially program Trimble eCognition Developer software to analyse digital photographs and identify soil objects on a white clothing fabric background (Trimble Geospatial, 2017). This software was also programmed to identify a limited palette of 25 Munsell soil colours (Munsell Color Company, 2009). The dominant Munsell colour of each individual or aggregate soil object was analysed; enabling numerical data to be graphically represented. To increase the accuracy of results, standardised numerical data on the colour and shape of soil objects for analysis was limited to soil objects ≥100μm/2 pixels. A white scale bar in each photograph was used as a colour standard to calibrate image processing software and provide a more accurate analysis of the Munsell soil colour of trace soil objects transferred. With limited programming, image processing software was proven capable of precisely recording a very similar range of Munsell soil colours for trace soil patterns on multiple items of clothing originating from each individual soil type.

The ability of image processing software to identify directionality of trace soil transferred and provide numerical data for a graphical representation in Rose diagrams provides forensic soil scientists with an objective method of analysing method of soil transference (Holcombe, 2011). This research documented distinct differences in directionality when soil was transferred by dragging a simulated clothed human body across a soil surface or the body was merely placed upon the soil surface. A strong bimodal directionality was recorded for clothing fabric dragged across a soil surface due to the presence of a raised middle seam on all clothing samples tested that was positioned near-perpendicular to the direction of movement. When the same type of clothing fabric was merely placed upon the same soil surface, no definite directionality was recorded. The methodology used in dragging and placing experiments was simplified to minimise any additional movement that might distort the results.

Although it can be argued that the nature of forensic reconstruction is to work with ‘inferences’, image analysis using image processing computer software may provide a ‘ground truth’ to test the objectivity of ‘naked eye’ visual analyses of trace soil evidence.

6.1 Limitations

Due to ethical considerations in experimental design, this forensic research has used analogues to simulate circumstances that may occur at real forensic scenarios. Likewise, these laboratory and field experiments could only simulate a clothed human body being dragged or placed on a soil surface. Methodology of laboratory experiments was tightly controlled; to minimize the influence of external factors that could decrease consistency of results or potentially camouflage trends. This tight control did not accurately mimic what might confront forensic examiners at a real crime scene. It may be argued that the field experiment using the clothed human rescue dummy at RTBG came closest to replicating realistic soil transfer patterns that might occur on clothing fabric when a female victim wearing a bra is dragged or placed on a soil surface at a crime scene. However, only two methods of soil transference and a relatively limited number of different soil types were tested. The rescue dummy was not made of organic flesh and bone and its weighted, padded body was covered by heavy-duty synthetic overalls. Therefore, although the rescue dummy provided the realistic weight and general shape of a human body, it could not accurately mimic an incapacitated or dead female victim. One option might be to dress a pig carcass up in clothing of different fabric types and test different soil transfer methods. Another more adventurous option might be to run trace soil experiments using recently donated male and female cadavers of varying weights and body types at a 'body farm'.

At its current level of programming, the image processing software could not differentiate reddish-brown organic particles such as plant bark or dark leaf matter from reddish-brown mineral-based soil particles. The software could not reliably delineate the elongate outline of a 0.5cm stalk of straw if encroached by mineral soil aggregates. Soil objects with an area less than 2 pixels were excluded from sorted results because the software could not reliably classify objects less than 100 by 50 microns. The software had some difficulty identifying the perimeter of areas of dark-coloured objects from adjoining shadows on the fabric. When analysing photographs taken in the field under the shade of surrounding vegetation, dark areas of shadow were incorrectly classified as dark coloured soil objects by the software. These shadow areas had to be cropped out before the remaining fabric area could be accurately classified. If the fabric colour had not been homogenous, this task would have been much more challenging.

Source digital photographs were only 14.1 megapixels. A basic digital camera was used to simulate the minimal equipment available to first responding uniform police officers attending crime scenes; who might only have the camera on their mobile phone to take initial photographs of trace soil evidence.

6.2 Future research

Future research could be directed to a more accurate analysis of Munsell colour results by programming image processing software to recognise the full range of 450 Munsell soil colours (Bigham & Ciolkosz, 1993; Debret et al., 2011; Lynne & Pearson, 2000; Moritsuka, Matsuoka, Katsura, Sano, & Yanai, 2014; Munsell Color Company, 2009; Sugita & Marumo, 1996). A more inclusive range of common clothing fabric types, textures, colours and patterns and combinations of different soil transfer methods, more realistic of real crime scenarios, will need to be tested using image processing software or other methods of visual analysis; to provide forensic soil scientists or crime scene investigators with a thorough understanding of trace soil patterns of suspects or victim's clothing.

Future development of fully-automated image processing software for analysing trace soil evidence on not only clothing fabric but other items such as shoes, car tires, carpet and furniture would enable an operator untrained in forensic soil science to identify evidence potentially of use to a criminal investigation (See Munsell Color online article in Appendix 7.3).

Most forensic laboratories do not test all clothing items associated with a major crime for soil evidence. This may be due to a massive backlog of soil evidence from other cases awaiting analysis, a lack of funding, limited access to XRD instruments or lack of technical expertise. If image processing software was developed to provide police with a cheap, quick, accurate and accessible method of 'in-house' analysis of soil evidence on clothing, trace soil analysis may become as routine as DNA testing and fingerprint analysis. This image processing method might also be used to uncover new forensic soil evidence in cold case crimes for police to investigate (Murray, Fitzpatrick, Kobus, Berry, & Bottrill, 2017). It might also be useful to provide an online guide to the naked eye and image processing techniques used in this thesis to identify trace soil patterns on clothing fabric and interpret their method of transfer; as well as photographic tips to best record pristine trace soil patterns on clothed bodies at a crime scene. Translations of this online guide in languages other than English would enable police investigators worldwide to make use of these methods of forensic soil analysis.

Other potential avenues for future research may be to adapt the soil transference methods tested in this thesis to investigate how burying a clothed body affects the persistence of soil transfer patterns on clothing (Ueland, Nizio, Forbes, & Stuart, 2015).

To deliver this vital forensic soil information in future, the following issues should be addressed:

a) Develop and produce on a commercial scale affordable and fully automated image processing computer software, with an online help manual translated in all major languages. The help manual would teach the operator how to use image processing software to analyse digital photographs of trace soil patterns on clothing fabric. Image software would be programmed to produce numerical data on trace soil patterns, to produce understandable graphs detailing the Munsell soil colour range and quantity of trace soil objects transferred (Munsell Color Company, 2009). Rose diagrams would be incorporated into the software to illustrate whether soil objects show any directionality in their placement on fabric (Holcombe, 2011). This would also help to indicate the method of transfer and whether the victim was struggling or incapacitated when their body made contact with a soil surface.

b) Provide an online and/or printed guide to the naked eye techniques used in this thesis to identify trace soil patterns on clothing fabric and interpret their method of transfer; as well as photographic tips to best record pristine trace soil patterns on clothed bodies at a crime scene.

c) Produce a grey scale bar to provide the necessary scale when taking digital photographs of soil evidence on clothing and to act as a colour standard. This would not only allow police to compare the sizes of trace soil objects, but also enable image processing software to correctly analyse the dominant and subdominant Munsell soil colour range of trace soil on clothing; regardless of the natural or artificial lighting conditions at the crime scene or the digital camera used.

In summary, this research may provide the first step to developing a database of trace soil patterns testing different transfer methods, soil types and fabrics. If police forensic personnel and forensic soil scientists adapted current crime scene protocols to include digital photographs of trace soil evidence on bodies, clothing and other items of interest before they are handled or transported from the crime scene, a pristine record of soil evidence may be available to assist police in reevaluating criminal cases in the future. New forensic protocols would need to be developed to 'future-proof' evidentiary images by considering potential advances in digital technology. The initial experimental findings documented in this thesis has indicated possible issues with current forensic methods used to record, handle and transport trace soil evidence at crime scenes and forensic laboratories. It is hoped that this research may provide the catalyst for wider debate amongst police investigators and forensic soil scientists.

6.3 References

Aardahl, K. (2003). *Evidential Value of Glitter Particle Trace Evidence.* (Masters), National University, San Diego, CA.

Aardahl, K., Kirkowski, S., & Blackledge, R. (2005). A target glitter study. *Sci. Just., 45*(1), 7-12. doi:http://dx.doi.org/10.1016/S1355-0306(05)71615-4

Bergslien, E. (2012). *An Introduction to Forensic Geoscience.* USA: Wiley-Blackwell.

Bigham, J., & Ciolkosz, E. (1993). Soil Color. *SSSA Special Publication, 31*, 159.

Bull, P., Morgan, R., Sagovsky, A., & Hughes, G. (2006). The transfer and persistence of trace particulates: experimental studies using clothing fabrics. *Sci. Just., 46*(3), 185-195. doi:http://dx.doi.org/10.1016/S1355-0306(06)71592-1

Bull, P., Parker, A., & Morgan, R. (2006). The forensic analysis of soils and sediment taken from the cast of a footprint. *Forensic Sci Int, 162*(1-3), 6-12. doi:http://dx.doi.org/10.1016/j.forsciint.2006.06.075

Debret, M., Sebag, D., Desmet, M., Balsam, W., Copard, Y., Mourier, B., . . . Winiarski, T. (2011). Spectrocolorimetric interpretation of sedimentary dynamics: The new "Q7/4 diagram". *Earth-Science Reviews, 109*, 1-19. doi:http://dx.doi.org/10.1016/j.earscirev.2011.07.002

Di Maggio, R., Al Naimi, K., Barone, P., Salvador, F., Dawson, L., Dixon, R., . . . Villalba, D. (2017). Global developments in forensic geology. *Episodes Journal of International Geoscience, 40*(2), 120-113. doi:http://dx.doi.org/10.18814/epiiugs/2017/v40i2/017014

Fitzpatrick, R. (2011). The value of soil in criminal investigations. *Soil Forensics profile Newsletter,* 5-6.

Fitzpatrick, R. (2013a). Demands on soil classification and soil survey strategies: special-purpose soil classification systems for local practical use. In F. Taha & M. Abdelfattah (Eds.), *Developments in Soil Classification, Land Use Planning and Policy Implications: Innovative Thinking of Soil Inventory for Land Use Planning and Management of Land Resources* (pp. 51-83). Netherlands: Springer.

Fitzpatrick, R. (2013b). Soil: forensic analysis. In A. Jamieson & A. Moenssens (Eds.), *Wiley Encyclopedia of Forensic Science*. Chichester, West Sussex.

Fitzpatrick, R. (2015). *Analyses of four questioned soil samples on a pyjama top and fourteen control samples from the Onkaparinga river region relating to the Louis Bell investigation by SAPOL*. Retrieved from Adelaide, South Australia:

Fitzpatrick, R., & Raven, M. (2010). *Investigation of soils and brick samples relating to Operation Dargan*. Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_061. 29 September 2010. 53pp. Appendix A1 (9pp); Appendix A2 (115pp); Appendix A3 (159pp). (Total 328pp).

Fitzpatrick, R., & Raven, M. (2012a). How pedology and mineralogy helped solve a double murder case: using forensics to inspire future generations of soil scientists. *Soil Horizons, 53*(5), 14-29. doi:http://dx.doi.org/10.2136/sh12-05-0016

Fitzpatrick, R., & Raven, M. (2012b). *The State of Western Australia v. Lloyd Patrick Rayney Trial: Request for Supplementary Statement Relating to Extraction of Particulate Material from Bra.* Retrieved from Centre for Australian Forensic Soil Science.

Fitzpatrick, R., & Raven, M. (2016). *Guidelines for conducting criminal and environmental soil forensic investigations: Version 10.1*. Retrieved from South Australia:

http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=35757;m=view

Fitzpatrick, R., Raven, M., & Forrester, S. (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). Netherlands: Springer Netherlands.

Fitzpatrick, R., Raven, M., & Self, P. (2011). *Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to operation Dargan*. Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_080. 27 May 2011. 116pp.

Fitzpatrick, R., Raven, M., & Self, P. (2012). Soil as significant evidence in a sexual assault case. In L. Burkitt & L. Sparrow (Eds.), *Proceedings of the 5th Joint Australian and New Zealand Soil Science Conference: Soil solutions for diverse landscapes*. Hobart: Australian Society of Soil Science Inc.

Fitzpatrick, R., Raven, M., & Self, P. (2014, 3-5 February, 2014). *Clay mineralogy as significant evidence in 4 murder investigations involving a wide range of earth materials from Perth, Adelaide, Melbourne and Sydney.* Paper presented at the Proceedings 23rd Australian Clay Minerals Society Conference, Perth.

French, J., Morgan, R., Baxendell, P., & Bull, P. (2012). Multiple transfers of particulates and their dissemination within contact networks. *Science and Justice, 52*(1), 33-41. doi:http://dx.doi.org/10.1016/j.scijus.2011.05.001

Hicks, T., Vanina, R., & Margot, P. (1996). Transfer and persistence of glass fragments on garments. *Sci. Just., 36*(2), 101-107. doi:http://dx.doi.org/10.1016/S1355-0306(96)72574-1

Holcombe, R. (2011). GEOrient. Queensland, Australia: School of Earth Sciences, University of Queensland.

Lepot, L., Vanden Driessche, T., Lunstroot, K., Gason, F., & De Wael, K. (2015). Fibre persistence on immersed garment - Influence of knitted recipient fabrics. *Science and Justice, 55*, 248-253. doi:http://dx.doi.org/10.1016/j.scijus.2015.02.006

Lynne, W., & Pearson, M. (2000). The color of soil. *The Science Teacher* (May). Judgement Summary: The State of Western Australia v. Rayney, 404 (INS 83 of 2011) 1-13 (WASC 2012a). The State of Western Australia v. Rayney, 404 1-369 (WASC 2012b).

McDermott, S. (2013). Trace evidence: transfer, persistence and value. In J. Siegel (Ed.), *Encyclopedia of Forensic Sciences* (second ed.). Waltham, MA: Academic press.

Morgan, R., & Bull, P. (2007). Forensic geosciences and crime detection: Identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale, 127*(2),73-89.

Morgan, R., Cohen, J., McGookin, I., Murly-Gotto, J., O'Connor, R., Muress, S., . . . Bull, P. (2009). The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Sci. Just. ,49*(4), 277-285. doi:http://dx.doi.org/10.1016/j.scijus.2009.02.004

Morgan, R., French, J., O'Donnell, L., & Bull, P. (2010). The reincorporation and redistribution of trace geoforensic particulates on clothing: an introductory study. *Science and Justice, 50*(4), 195-199. doi:http://dx.doi.org/10.1016/j.scijus.2010.04.002

Moritsuka, N., Matsuoka, K., Katsura, K., Sano, S., & Yanai, J. (2014). Soil color analysis for statistically estimating total carbon, total nitrogen and active iron contents in Japanese agricultural soils. *Soil Science and Plant Nutrition, 60*(4), 475-485. doi:http://dx.doi.org/10.1080/00380768.2014.906295

Munsell Color Company. (2009). *Munsell Soil Color, Book*. Michigan: Munsell Color X-rite.

Murray, K., Fitzpatrick, R., Bottrill, R., Berry, R., Woolley, R., Doyle, R., & Kobus, H. (2015). *Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: laboratory dragging experiments*. Retrieved from Adelaide: http://www.adelaide.edu.au/directory/robert.fitzpatrick

Murray, K., Fitzpatrick, R., Bottrill, R., Berry, R., & Kobus, H. (2016). Soil transference patterns on bras: Image processing and laboratory dragging experiments. *Forensic Science International, 258*(January 2016), 88-100. doi:http://dx.doi.org/10.1016/j.forsciint.2015.10.009

Murray, K., Fitzpatrick, R., Bottrill, R., & Kobus, H. (2017a). An investigation of the pattern formed by soil transfer when clothing fabrics are placed on soil using visual examination and image processing analysis. *Forensic Science and Criminology, 2*(1), 1-11. doi:http://dx.doi.org/10.15761/FSC.1000110

Murray, K., Fitzpatrick, R., Bottrill, R., & Kobus, H. (2017b). Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations. *Forensic Sci International, 276*, 24-40. doi:http://dx.doi.org/10.1016/j.forsciint.2017.03.026

Murray, K., Fitzpatrick, R., Bottrill, R., & Kobus, H. (2017c). Soil transference patterns on clothing fabrics and plastic buttons: image processing and laboratory dragging experiments. *Forensic Science and Criminology, 2*(1), 1-12. doi:http://dx.doi.org/10.15761/FSC.1000109

Murray, K., Fitzpatrick, R., Kobus, H., Berry, R., & Bottrill, R. (2017). Using soil color analysis for forensic application at a crime scene. *Color & Science*. Retrieved from Munsell Color website: http://munsell.com/color-blog/color-analysis-forensic-application-crime-scene/

Palmer, R. (2014). Fibers: Transfer, persistence and recovery *Wiley Encyclopedia of Forensic Science* (pp. 1-10).

Pounds, C., & Smalldon, K. (1975a). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. III: A preliminary investigation of the mechanisms involved. *J. Forensic Sci. Soc., 15*(3), 197-207. doi:http://dx.doi.org/10.1016/S0015- 7368(75)70985-4

Pounds, C., & Smalldon, K. (1975b). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part I: Fibre transference. *J. Forensic Sci. Soc., 15*(1), 17-27. doi:http://dx.doi.org/10.1016/S0015-7368(75)70932-5

Pounds, C., & Smalldon, K. (1975c). The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part II: Fibre persistence. *J. Forensic Sci. Soc., 15*(1), 29-37. doi:http://dx.doi.org/10.1016/S0015-7368(75)70933-7

Roux, C., & Robertson, J. (2013). Fibers. In J. Siegel (Ed.), *Encyclopedia of Forensic Sciences* (second ed.). Waltham, MA: Academic Press.

Scott, K., Morgan, R., Jones, V., & Cameron, N. (2014). The transferability of diatoms to clothing and the methods appropriate for their collection and analysis in forensic geoscience. *Forensic Sci International, 241*, 127-137. doi:http://dx.doi.org/10.1016/j.forsciint.2014.05.011

Stoney, D., & Stoney, P. (2015). Critical review of forensic trace evidence analysis and the need for a new approach. *Forensic Sci International, 251*, 159-170. doi:http://dx.doi.org/10.1016/j.forsciint.2015.03.022

Sugita, R., & Marumo, Y. (1996). Validity of color examination for forensic soil identification. *Forensic Sci*

International, 83(3), 201-210. doi:http://dx.doi.org/10.1016/S0379-0738(96)02038-5
Trimble Geospatial. (2017). eCognition Developer 9. *Trimble Innovation Program.* Retrieved from http://www.ecognition.com/suite/ecognition-developer
Ueland, M., Nizio, K., Forbes, S., & Stuart, B. (2015). The interactive effect of the degradation of cotton clothing and decomposition fluid production associated with decaying remains. *Forensic Sci International, 255*, 56-63. doi:http://dx.doi.org/10.1016/j.forsciint.2015.05.029

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Interpreting the transfer method of soil evidence on clothing by identifying trace soil patterns

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In a recent homicide in Western Australia, trace fragments of brick particles (often <0.5mm) and soil on the victim's clothing suggested she was initially attacked in her front yard and not in Kings Park where her body was buried [1]. The trial was before a judge only and he concluded that the mineralogical data from the brick particles on the victim's clothing and the bricks from her front driveway suggested she was initially attacked in her front yard and not in Kings Park [2, 3]. However the important issue that emerged during the trial was how the brick and soil particles were transferred to her clothing [2, 3]. During forensic analyses of soil materials on clothing, especially when there are few soil materials present it is often necessary to remove as much soil material as possible from clothing for mineralogical and chemical analysis. The unintentional effect of this forensic testing, (which in this case also included cutting up the victim's clothing) was the near-complete removal of trace soil patterns that may have enabled a better understanding of the circumstances befalling the murder victim. This became the catalyst for designing a range of laboratory [3] and field soil transference experiments on clothing fabrics to study, recognise and classify soil patterns transferred onto fabric when a body is dragged across a soil surface.

Using a series of laboratory experiments [3] and a simulated clothed human body, nearly 1000 experiments tested the soil transfer methods of either placing or dragging weighted fabric on a wet or dry soil surface. Sets of trace soil patterns were recorded; with many patterns unique to a specific method of soil transference. Twenty different anthropogenic and natural soil types and five fabric types [cotton, nylon, nylon-elastane, polyester-cotton and polar fleece (polyester brushed both sides)] were used to ascertain whether some trace soil patterns could universally occur across all soils and fabrics tested. Soil mineralogy and moisture content, irregularities on the fabric surface (such as raised seams) and appendages (such as buttons and metal buckles) had a greater influence on resulting trace soil patterns than the five fabrics tested. This influence was also dependent on the method of soil transfer used. Image processing computer software provided a cheap, accessible, objective and standardised method of providing numerical data on trace soil transferred to fabric. This analysis included Munsell soil colour analysis, the quantity and directionality of individual and aggregate trace soil objects. Digital photographs were taken using a camera in natural and artificial lighting conditions of trace soil patterns on fabric. It was important that this occurred before the simulated clothed body was moved or clothing fabric removed; to keep trace soil patterns in original pristine condition.

References:

[1] Fitzpatrick R.W., Raven M, Self P.G. (2011) Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to Operation Dargan. Centre for Australian Forensic Soil Science Restricted Client Report No. CAFSS_080. 27 May 2011. 116pp.

[2] Martin B. The State of Western Australia v. Rayney. [No 3]: WASC; 2012. p. 1-369.

[3] Martin B. Judgement summary: The State of Western Australia v. Rayney. [No 3]: WASC; 2012. p. 1-13.

[4] Murray, Kathleen R, Fitzpatrick Robert W, Bottrill Ralph S, Berry Ron, Kobus Hilton. (2016) Soil transference patterns on bras: Image processing and laboratory dragging experiments. Forensic Science International. 258, 88-100. http://dx.doi.org/10.1016/j.forsciint.2015.10.009

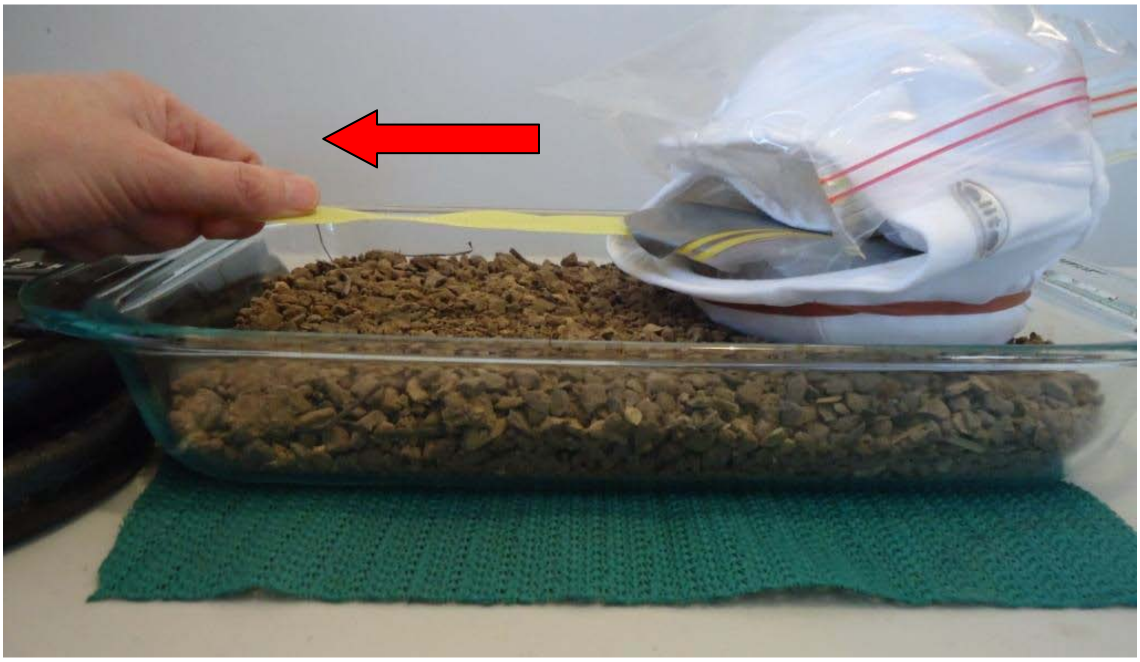
7. APPENDIX REPORT AND SUPPLEMENTARY DATA

7.1 Soil patterns on bra fabrics dragged across different soil surfaces using image analyses: Laboratory dragging experiments

Acid Sulfate Soils Centre

Soil patterns on bra fabrics dragged across different soil surfaces using image analyses:

Laboratory dragging experiments



K. R. Murray, R.W. Fitzpatrick, R. Bottrill, R. Berry, R. Woolley, R. Doyle and H. Kobus

Acid Sulfate Soils Centre Report: ASSC_096 (V13)

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Cover image

Weighted bra dragged from right to left over soil material during a three second count soil transference experiment. Sections of bra that are not subjected to being dragged over the soil during the experiment remain clean inside a clip-lock plastic bag on top of the weight. The glass Pyrex dish containing soil material and weighted bra is placed on a nonslip mat and a backstop of weights on the left to stop it moving during the transference experiment.

Photographer: Kathleen Murray @ 2014 Acid Sulfate Soils Centre, The University of Adelaide

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EXECUTIVE SUMMARY

Key forensic science evidence in a 2012 homicide case included the results of soil examinations. While the soil comparisons that indicated source were not in question, the process of how the soil was deposited on the victim's clothing became a significant factor. It was alleged that the victim was dragged and that this was the mechanism of transfer. However there was no published research available that identified characteristics typical of dragging and the court could not be satisfied that some other mode of transfer had not occurred. The work described in this report was undertaken to provide knowledge that would assist in interpretation of soil transfer in criminal events.

The soil evidence in the homicide case was principally located on the victim's bra. Weighted bras were used in these STEs, to simulate a female victim dragged across a soil surface. Soil transfer to bra shoulder-straps and cups was studied. Shoulder straps were chosen because this area retained the most soil evidence in the aforementioned murder case; while bra cups provided a large area to aid in the initial investigation of soil transfer patterns.

Eighty-four (84) experiments used anthropogenic and natural soils from the Royal Tasmanian Botanical Gardens, Hobart, Tasmania, Australia. Four soil samples used were anthropological [otherwise known as Technosols or human altered/human transported (HAHT)] soils; including one brick sample. One sample was a mixture of HAHT and natural soils, and two samples were natural soil types. Six soils were sampled from 0-10cm depth. One natural soil sample, made from undecomposed leaf matter, was taken from 0-5cm above the soil surface.

Using nylon-elastane bras and either wet or dry soil from seven distinct samples, the soil transfer patterns produced during the experiments were identified in situ by naked eye alone, or with the aid of a microscope. Soil transfer patterns were photographed in situ using a 14 megapixel digital camera and provided an accurate record of the trace soil evidence. Microscopic analysis and photomicrographs of soil transfer patterns followed, with the firmly attached weight preserving the soil transfer patterns through increased stability of the flimsy bra fabric. Once clothing is moved, results indicated that loose soil particles that help define the often very delicate soil transfer patterns are lost; or deposited in the bottom of an evidence bag.

The soil transference experiments identified eight patterns specific to dragging as the method of transfer. These transfer patterns were largely dependent on a wide range of soil features that were measured and identified for each soil tested using X-Ray Diffraction and DNIR analysis. STEs consistently resulted in soil building up on clothing seams, strap edges and to a lesser extent, fluffy seams. Soil 'trails' consistently provided strong evidence of fabric being dragged across a soil surface. A fine dusting of soil appeared on metal bra shoulder-buckles when very dry soil was tested. In contrast, when wet soil was used, the metal buckle was either completely clean or had muddy aggregates adhering to an otherwise wet shiny surface. The dragging method used in these experiments trapped soil in front of the metal buckle and left characteristic 'plough' marks in the soil surface behind. The alignment of elongated particles of soil with the direction of drag was also noted in the laboratory. However, this pattern had to be documented in situ; because the slightest movement of particles or fabric by air-conditioning could destroy the alignment. For this reason, this transfer pattern was the least consistent and should not be relied upon outside of a controlled laboratory environment.

The majority of soil particles transferred in all STEs were very fine silt or clay-sized fragments. The largest fragment transferred was a 5mm x 4mm brick fragment.

Six of the eight soil transference patterns were produced by the transfer method of dragging with 100% consistency in wet and dry soil runs across the seven soil samples; depending on soil moisture content, particle size and mineralogy, some patterns were easier to visually identify than others. Another two patterns that appeared intermittently involved the alignment of elongated particles parallel to the direction of movement and a comparison of the quantity of soil transferred onto fluffy-textured versus smooth finely-woven fabric.

Image processing software analysed digital photographs of soil transference patterns on fabric. All soil objects transferred with a diameter of 2 pixels and above underwent an object-oriented classification. Trace soil from one of seven soil samples were identified using a Munsell colour range with similar diominant and sub-dominant peaks of specific Munsell colours.

Image processing numerical data gathered on the quantity of soil transferred to fabric enabled a relationship to be discovered between soil type, clay (smectite), particle size and soil moisture content. Soil type (e.g. gravelly, sandy, loamy or organic-rich soil), clay (smectite) and soil moisture content were the greatest influencing factors in all the dragging soil transference tests (both visual with the naked eye and measured properties) to explain the eight categories of soil transference patterns.

Key findings and future work

In order to increase our understanding of the universality of soil transfer patterns, which underpin key findings in this research, it was necessary to examine how soil mineralogy, carbon and sulfur content may influence resulting soil transfer patterns. X-ray diffraction (XRD) analysis was used to compare and contrast mineralogy of the original soil samples used in the STEs. Carbon and sulfur content was determined through Nondispersive infrared (NDIR) analysis.

The texture of soil samples ranged from loamy to clayey. NDIR identified carbon levels of up to 3.10% in the gravel-rich HAHT soils, 14% for the Rose garden bed HAHT soil and 22.8% in the natural soil. No Sulfur-bearing species were identified. Further testing of soils from vastly different origins would be required to confirm the universality of the patterns documented in this paper. But initial results are extremely promising that the trace soil patterns that occur when weighted fabric is dragged across a soil surface, would be seen to a greater or lesser extent in all soil types.

Image processing computer analysis of digital photographs taken *in situ* of trace soil transfer patterns on fabric provided an object-oriented image classification of soil objects transferred. Although soil transfer patterns were easily identifiable by naked eye alone, image processing software provided objective numerical data to support our conclusions. Using Trimble eCognition Developer software, all soil objects (both individual grains and aggregates from 2 pixels/≥100microns diameter) were mapped on the fabric surface. Each soil transfer pattern was analysed for its unique range of Munsell soil colours, directionality of soil clumps and stains and quantity of different categories of soil particles. Image processing software thereby enabled the collation of more comprehensive, objective and quantifiable numerical data than could be produced through the interpretation of soil transfer patterns by naked eye alone.

Image processing also provided a more comprehensive Munsell Soil colour analysis to identify and compare trace soil on fabric to other trace soil evidence from the same location. There is tremendous potential for image processing analysis to accurately identify and compare the Munsell soil colour of trace soil evidence on fabric without requiring a spectrophotometer. For example, this robust approach and methodology enables Munsell soil colours and other distinctive characteristics of soil morphology of trace amounts of soils on fabrics to be better interpreted in a court of law.

These new methods of forensic soil investigation provide a direct interpretation of the circumstances behind clothing making contact with a soil surface at a crime scene. Digital photographs taken of trace soil evidence and analysed by image processing software, have the potential to accurately compare trace soil evidence on both victim's and suspect's clothing. These forensic soil analyses do not require expensive equipment or highly trained personnel (e.g. scanning electron microscopy). This initial stage of analysis can potentially be done by Police and Forensic scientists with a very limited knowledge of soil science. Once the soil transfer patterns are recognised and categorised using the image processing software, this information will provide a more quantitative indication of whether trace soil evidence on a victim's clothing is similar or dissimilar to soil evidence on suspects' clothing, Police can decide whether the soil evidence warrants further investigation via more expensive and time-consuming techniques.

1. INTRODUCTION

Summary

This section gives a brief and selective overview of the purpose for conducting soil transference experiments on bra fabrics.

1.1 Overview and purpose

In the Australian Rayney murder case (Martin 2012b, 2012a), there were no fingerprint or DNA evidence or reliable witness testimony to help Police solve this complex murder case. Soil evidence on the victim's bra became vital in discovering and proving the circumstances and location of the initial attack as being the front yard of the victim's home (Fitzpatrick *et al.* 2011; Martin 2012b). Soil evidence on victim's bra remained uncontaminated from other soil sources, despite the victim being buried for eight days at a second location containing a completely different soil type. The CAFSS report and presentations/cross examination in the Perth Supreme court provided a "predictive, soil-regolith model, from microscopic to landscape scale", which established that soil and brick particles/fragments found on the victim's clothing and hair (via two seed pods) originated from the front yard of the victim's home at Como in Perth. The Judge (Justice Martin) agreed with this assessment, as indicated in the following 2 paragraphs of his 369 page report (Martin 2012b, 2012a): "Para 1136 - In broad summary, the soil and artefacts recovered from the deceased and her clothing provide a significant link between the deceased and the home at Como." However, CAFSS were not able to provide evidence during the court hearing on how the brick particles/fragments were transferred to the bra, especially within the elasticised bra-straps. Instead, CAFSS were requested by the Prosecution Council during the trial to provide a supplementary statement on the extraction of the particulate material from the bra (Fitzpatrick and Raven 2012b) for use by State forensic laboratories to conduct soil transference experiments or to provide a statement on possible mechanisms for soil transference to the bra.

The complex circumstances of this murder investigation provided the impetus for conducting a series of systematic soil transference experiments on clothing (bra cups). The prime objective of this study was to develop and conduct more quantitative soil transference experiments based mainly on the methods developed by Pounds and Smalldon (Pounds and Smalldon 1975b, 1975c, 1975a). This will assist forensic examiners to better interpret soil evidence discovered on clothing at crime scenes, especially to establish if a clothed victim has been dragged across a soil surface (Pye 2007; Ruffell and McKinley 2008; Murray 2011). Consequently, the aim of this work was to investigate and develop methods to better quantify soil transfer patterns on a bra using a wide range of representative anthropogenic [otherwise known as human altered/human transported (HAHT) soils or Technosols, which includes brick fragments] and natural soils.

The objectives of this study were to undertake a range of laboratory dragging experiments that involved: (i) testing twenty one (21) weighted bras to evaluate the persistence, size and quantity of soil transferred, (ii) eighty-four (84) soil transference experiments (STE) were run on these bras and (iii) detailed analyses of digital photographs of the resulting soil transfer patterns on the bra cup fabric using image processing software to quantify different trace soil patterns on the fabric that was transferred from different soil locations.

False and/or incomplete criminal reports are a reality for law enforcement officials, waste police, forensic and judicial resources and can lead to possible miscarriage of justice (Taupin 2000; Rumney 2006). Identifying the exact cause or mechanism of soil transference and damage to clothing is difficult, and often the presence of soil and damage to fabrics is the only form of forensic evidence. In the context of soil forensic examinations, the most frequent damage to clothing is likely to be caused by dragging over a range of soil surfaces. A number of factors may influence the "severance morphology" in damaged fabrics such as: (i) the fibre content and fabric structure (e.g. elasticised fabrics) and (ii) soil type. Understanding soil transference and damage to clothing is important to support criminal investigations. Investigating damage and transference to fabrics has traditionally been done using low power microscopy and more recently has also incorporated Scanning Electron Microscopy (SEM) (Pelton 1995, 1998). However, SEM methods have limitations mainly because of: (i) the small size of sample required to be examined in the SEM, (ii) sample pre-treatments are required (i.e. method is partly destructive and (iii) the high cost for SEM analyses. Consequently, the preferred method involved using digital photographs taken *in situ* of the whole bra that was subjected to the dragging experiment followed by selective observations using a low-powered binocular microscope so as to ensure: (i) a "non-destructive soil pattern" on the bra, (ii) rapid and reliable testing, (iii) very little or no sample preparation (iv) and (v) relatively low cost of testing and analyses.

1.2 What is Forensic Soil Science?

The science of soil characterisation for forensic purposes can be significant in helping police solve crime, especially when no fingerprint or DNA evidence is available. The primary aim of forensic soil analysis is to associate a trace soil sample transferred onto an item with a specific location. Items that are routinely examined include clothing, shoes, vehicles and tools including shovels and rakes (Fitzpatrick 2013b; Fitzpatrick and Raven 2013).

When two surfaces come into contact, there is the potential for the mutual transfer of material between them (Locard 1930). It is the task of the forensic scientist to recognize and classify these minute particles of trace evidence.

Soil has been called the ideal trace evidence (Aardahl 2003). It is nearly invisible to the casual observer and the myriad of variables in mineralogy and morphology provide soil with the uniqueness of a human fingerprint. There are more than 50,000 different varieties of soil in the United States alone; and each soil variety will also differ at individual locations due to the soil's parent material, microclimate and unique ecosystem of organisms (Fitzpatrick 2008). The amount of time required for all of these soil-forming properties to create changes can take as little as weeks to thousands of years. Soil does not only alter laterally either. It also alters vertically (Fitzpatrick 2013a). Surface soil is most likely very different to soil occurring at one metre down.

There is an excellent chance that trace soil will be transferred onto any object that comes in contact with it; and that some fine (<2mm) particles will persist as soil evidence. Analysis of this soil evidence can be performed rapidly using inexpensive equipment and non-specialist practitioners (Fitzpatrick *et al.* 2009).

When soil from one location is transferred to a suspect or victim's clothing or belongings, this is referred to as a primary transfer. Secondary transfers, such as when soil from a victim's clothing is transferred to a suspect's clothing whist moving the body, can also provide valuable evidence linking a suspect to a crime scene (Morgan and Bull 2007).

Trace soil evidence found on clothes, shoes, vehicles and property can not only implicate suspects in the execution of a crime, but clear potential suspects and support their alibis (Fitzpatrick and Raven 2012a; Fitzpatrick *et al.* 2012b). Soil evidence has helped Police to solve decade old murders and cleared prime suspects of any involvement; enabling the innocent to mentally resume their lives and the guilty to face a court of law for their crimes (Fitzpatrick *et al.* 2012a).

Natural soil materials include minerals, organic matter and rock fragments, whereas human-made (known as Anthropol/Technosol or HAHT) soils may contain manufactured or exotic materials from different environments, such as glass, brick dust or small particles of concrete (Galbraith 2012). When HAHT material is discovered on clothing at a crime scene, or on the clothing of a suspect, it can provide forensic investigators with unique and distinct comparative evidence. Fine silt and clay-size fractions of soil (<50-100 μm) have the capacity to stick to the surface of fabric for weeks (Morgan and Bull 2007). Small amounts of fine soil evidence have often been missed by offenders who have attempted to destroy evidence that may incriminate them. Geoforensic scientists have located trace soil evidence embedded in clothing and shoes; even after being cleaned in a washing machine or dry cleaners (Bull *et al.* 2006a; Fitzpatrick *et al.* 2009; Fitzpatrick *et al.* 2014).

The current focus of forensic soil analysis is to create an accurate soil description using soil "colour, soil maps, soil minerals, soil biology (plant roots), soil chemical and physical properties, such as pH level or soil magnetism" (Fitzpatrick 2011). A detailed soil morphological characterisation of a sample's mineral and organic composition can be formed using X-ray diffraction (XRD), magnetic susceptibility, heavy mineral and magnetic fractionation (Murray *et al.* 2012). Forensic soil analyses compare and contrast controlled soil samples from a known site (such as a crime scene), questioned soil (unknown site) and alibi soil (suspect indicates a potential alibi location requiring forensic soil analysis) (Fitzpatrick and Raven 2013). As documented by Sugita and Marumo, variations in soil colour provide one of the most distinguishing characteristics of trace soil evidence (Sugita and Marumo 1996).

Rayney Murder Case

During the Rayney murder investigation in Western Australia, HAHT soil evidence pinpointed the location of the initial attack on the victim as occurring in her front yard. The morphology of soil particles adhering to two liquidambar seedpods caught in the victim's hair matched the human-made soil of her suburb of Como. The minus 20 micron fraction of yellow sand found embedded in her bra was consistent mineralogically with soil from the Rayney's front yard near their liquidambar tree. These fine fractions were distinctly different from the natural soil type of Kings Park where the victim's body was buried and subsequently discovered eight days later. The trace soil evidence in her bra was pristine and not contaminated with soil from the gravesite (Fitzpatrick and Raven 2012b).

Thirty-four (34) bricks, lightly coated with dirt, were taken from the Rayney's brick paving as control samples, to compare with the questioned traces of brick dust on the victim's clothing. Using advanced XRD techniques of particle acceleration known as "Synchrotron X-ray diffraction analyses" produced a high X-ray intensity that provided much greater sensitivity and resolution (Fitzpatrick 2012). Mineral particles were better separated in the poorly crystalline soils and bricks than is possible with standard XRD; in order to establish origin.

In his judgement summary, Judge Martin made particular mention of how locating the origin of 'particles of brick, paint and plastic on the deceased and her clothing' in the Rayney front yard convinced him beyond reasonable doubt that the initial attack had occurred there and not at the park where the body was found (Martin 2012b, 2012a). The uniqueness of HAHT trace soil evidence, combined with the last time the victim was seen alive, had narrowed the window of opportunity for committing the crime.

Morgan and Bull noted that a rapid decay rate of transference can quickly obliterate valuable trace evidence on some fabric surfaces (Morgan and Bull 2007). This decay rate is accelerated when the body or clothing is moved. Loose soil particles, including gravel-sized objects, simply fall off.

In investigating major crime, forensic laboratories across Australia, remove soil from clothing for analysis by rigorously shaking soil particles from fabric or even cutting soiled areas from clothing. It is routine procedure to try to extract as much soil as possible from fabric for analysis using such methods as X-Ray Diffraction. Valuable 'patterns' of transfer on fabric that document the circumstances behind soil making contact with the fabric surface are not identified or photographically recorded.

It was noted by Martin that when one forensic expert received the bra for forensic soil analysis, after previous forensic teams had rigorously tested the trace soil and the fabric itself, he declined to examine some areas in detail because "prior sampling and interference with the fabric construction might lead to incorrect conclusions" (Martin 2012b).

The current focus of forensic soil science on creating an accurate soil description, does not include a photographic record of trace soil patterns on the victim's clothing *in situ* before the body is moved or clothing removed. Any trace soil patterns on the victim's clothing that might have proven whether she was dragged or placed on soil surfaces in her back yard were, to our knowledge, never photographically documented and were destroyed during invasive testing processes over a four year period.

In his judgement summary, Judge Martin stated: “I do not accept the State case as to the dragging events. The major problem with the scenario constructed by the State is the absence of any evidence to support it” (Martin 2012a). Trace soil patterns on the victim’s clothing could have indicated the method of soil transfer and therefore, the circumstances during the attack.

Prosecution suggested the soil evidence may have been transferred to her clothing when she was lying on the back seat of her car when her killer drove her to Kings Park. Judge Martin suggested the soil evidence embedded in her bra may have wafted in during the ‘ordinary course of daily affairs’ (Martin 2012b).

Judge Martin also stated that “if the dragging events postulated by the State occurred, some signs of dragging or disturbance, particularly in the moss, would almost certainly have been left” (Martin 2012a).

A forensic soil examination of the Rayney front yard was not undertaken for weeks after the murder. During this time, periods of heavy rain and Police walking through the front yard and across the brick paving could have contaminated or destroyed any potential evidence of dragging soil pattern evidence on the paving or soil surface. This absence of pristine trace soil patterns on the victim’s clothing, combined with the lack of a detailed photographic record of the surrounding soil surfaces in the front yard dating from the time of the attack, became insurmountable weaknesses in the State’s case.

Until a detailed photographic record is routinely made of trace soil patterns on a victim’s clothing *in situ* at a crime scene, potential new forensic soil evidence indicating the circumstances of an attack will be degraded or destroyed. Morgan and Bull stated that ‘it is not only the identification of the components of a soil/sediment sample that enables the use of such evidence; it is of great importance that the interpretation of such analysis and their presentation to the court are accurate and meaningful’ (Morgan and Bull 2007).

With no fingerprint, DNA evidence or reliable witness testimony, these missing pieces of soil evidence became a major factor in the Rayney murder remaining unsolved. By using current methods of forensic soil analysis that begins in the laboratory and not at the crime scene, soil evidence alone could not be used to its true potential.

This reliance on expensive forensic soil testing procedures has further inhibited the use of soil analysis in forensic investigations. For forensic laboratories with all the latest analytical instruments, case volume is a major issue that can limit the scope of soil evidence investigated to major crime.

The need to focus on simple, inexpensive and rapid methods to record and analyse trace soil patterns, created by loose soil as well as soil embedded in fabric, has been an objective of these experiments. Using the methods described in this research, providing a pristine record of soil evidence *in situ* at a crime scene is easily achievable with a digital camera, scale bar and basic training. Therefore, analysis of soil evidence whilst still attached to a body, clothing or property should begin at the crime scene and not after soil evidence has been bagged up for transport to a laboratory or Police evidentiary storeroom. Visual analysis by human eye alone of digital photographs taken at the crime scene of soil evidence on clothing and any disturbed areas on the surrounding soil surface, followed by easily accessible computer image processing of these photographs, has the potential to revolutionise the use and accessibility of soil evidence in forensic investigations.

Morgan and Bull conclude that ‘if we do not learn from mistakes and do not take heed of comments and advice given in the past, then this current resurgence in the use of geoscience applications to forensic problems will once again fail to reach its full potential" (Morgan and Bull 2007). Forensic soil science that adds photographic records of trace soil patterns on clothing, shoes and property, as well as photographing soil surfaces at potential crime scenes, to its arsenal of chemical and morphological analysis, will fill the current void between analytical data and meaningful circumstances. This new vision for forensic soil science will not only help police solve crime, but better convict offenders in a court of law.

1.3 Review of previous research exploring the transfer of different particles onto textile fabrics

During the Rayney Murder investigation, a forensic expert, Mr Edmund Silenieks, began to experiment with the transference of brick dust from a red brick paver from the victim's front paving to 100% nylon knitted white fabric, resembling the fabric and weave of the victim's bra (Martin 2012b). The actual tag showing fabric composition was missing from the victim's bra, so this was an approximation of the actual bra fabric.

To test the transfer method of dragging, Mr Silenieks rubbed the fabric across the length of the paver applying 'firm hand pressure.' He then examined the fabric to discover that although the surface fabric appeared relatively clean, red brick particles had penetrated deep into the fabric, accumulating 'in the gaps between the loops and yarns' (Martin 2012b).

To test the transfer method of placing, Mr Silenieks took another piece of the same fabric and firmly pressed it onto the upper smooth surface of the paver 'using finger pressure for five seconds' (Martin 2012b). Only a few red brick particles were transferred, remaining solely on the upper surface of the individual yards.

These experiments were attacked by the Defendant's council for the following reasons (Martin 2012b):

1. Each experiment was done only once.

2. The force used during the transfer of the soil onto fabric was not measured and therefore not consistent.

3. The material used for the experiments was not close enough in composition and weave to the victim's bra

4. The test was not realistic because during the alleged dragging scenario, the victim was dragged for more than one brick-length.

5. The only other transfer method tested was placing the fabric on the brick surface.

6. These soil transfer experiments did not explore other scenarios that would explain the presence of numerous large coarse sand particles embedded in the victim's bra.

The Defendant's council then suggested that further transfer experiments should focus on dragging the fabric over other surfaces containing deposits of brick dust, such as the backseat of a car, pressing the fabric against a deposit of loose brick dust particles and dropping the fabric onto a deposit of loose brick dust (Martin 2012b).

Judge Martin agreed with Mr Silenieks' conclusion that the transfer method of dragging fabric across the brick surface caused the transfer of more brick particles than when the fabric was merely placed on the brick surface. However, he decided that the criticism made by the Defendant's council of Mr Silenieks' soil transfer experiments was also legitimate (Martin 2012b); leaving the circumstances behind the victim's clothing making contact with soil in her front yard still in doubt.

There has been no recent research focusing on the transfer of soil particles onto textile fabrics since Locard (1930). What follows below is a review of the transfer of mostly human-made particles such as powder, glitter, glass fragments, acrylic and wool fibres (McDermott 2013; Roux and Robertson 2013).

Bull *et al*. (2006b) built on the experiments of Pounds and Smalldon (1975a,b,c) who had originally explored the transfer and persistence of textile fibres. Bull *et al*. (2006b) documented the transfer and persistence of pollen, powder and metal particulates (glitter) on different types of materials; namely acrylic, cotton, denim, nylon, polyester and wool textiles (Bull *et al.* 2006b). A swatch of the textile to be tested was attached to a coat, which was worn indoors and out for seven days. In one experiment, pollen was brushed onto the textile swatch. In a second experiment, fluorescent powder was mixed with wheat flour and evenly distributed to the textile swatch. In a third experiment, lighter flint particles were flicked onto the swatch by striking the flint of a 'Clipper' lighter, Bull *et al*. (2006b) concluded that the fabric weave of the material played a larger part in the transfer and persistence of particulates than did the type particulate. The transference method had an initial effect in the quantity of particles transferred, but the persistence of these particles over time tended to level out. "No discernible difference was identified with any variant of material type, moisture level or grain size with regard to persistence, spreading capability, tenacity, transfer or detection during experimentation" (Bull *et al.* 2006b)

Hicks *et al.* (1996) explored the transfer and persistence of glass fragments on clothing, studying fragments transferred to the clothing of both the breaker standing 50cm away from the window glass and an accomplice standing 80cm away. Using either a hammer a stone or a pendulum, they discovered that up to seven fragments of glass could persist in clothing up to eight hours later. The number of fragments transferred depended upon the number of strikes, the distance between the windowpane and the person standing nearby, the time elapsed before forensic examination of the clothing and the weave of the garment (Hicks *et al.* 1996).

Unknown glitter particles persisting on clothing were compared to four known glitter types using light microscopy (Aardahl *et al.* 2005). They were characterised by end use, colour and shape to ascertain their relative uniqueness (Aardahl 2003). The majority of clothing tested had cosmetic glitter particles persisting, even if the wearer did not use any products containing glitter. The transference and persistence of these particles on human skin was reliant on the body's natural moisture. Adhesion was increased with the addition of petroleum jelly. Numerical data analysis was not attempted in this experiment, due to the large number of unknown variables.

In their ground-breaking experiments involving the transfer of fibres between acrylic and woollen knitted garments and a cotton lab coat, Pounds and Smalldon (1975a) concluded that three processes were involved in causing fibres to be transferred onto recipient garments (Pounds and Smalldon 1975a).

They established that during the first contact pass of transference, the majority of fibres transferred were loose short surface fragments or loose fibres pulled free by the friction of the contact. But during subsequent passes (eight contact passes in total), direct fragmentation of short fibres due to the pressure of the contact became the main cause of fibres being transferred; but at a rate of 50% less fibres than the initial first contact. The persistence of fibres on a garment worn up to thirty-four hours after first contact was not due to the electrostatic nature of the recipient garment fibres, but the strength of bond the remaining transferred fibres had made with the recipient garment (Pounds and Smalldon 1975a). They observed that after the first four hours of transference of fibre evidence to worn knitted garments, only 18% of the transferred fibres remained. After 34 hours, only 3% of transferred fibres remained, signifying the most strongly bonded fibres. On an old, smooth cotton lab coat, transferred evidence was mostly lost within 30 minutes of contact being made, indicating a rapid decay curve (Pounds and Smalldon 1975c).

Natural soil particles may transfer and persist differently on clothing than the human-made particles tested. Fine clay and silt-size fractions have a strong capacity to transfer and persist (Fitzpatrick 2011). Morgan and Bull (2007) noted that fine silt and clay size fractions of soil (<50-100 µm) have the capacity to stick to the surface of fabric for weeks (Morgan and Bull 2007).

Morgan *et al.* (2009) stated that 'in order for trace evidence to have a high evidential value, experimental studies which mimic the forensic reality are of fundamental importance. Such primary level experimentation is crucial to establish a coherent body of theory concerning the generation, transfer and persistence of different forms of trace physical evidence' (Morgan *et al.* 2009).

Using similar methodology to Pounds and Smalldon (1975a,b,c), fibre transference and persistence experiments, analogous experiments were designed to identify which factors influence the transfer, persistence and relative quantity of natural and human-made soil on clothing fabrics. Unlike Pounds and Smalldon, soil and not wool fibre transfer characteristics were tested. These new experiments also differed by focusing specifically on nylon-elastane bras; with the variable element being multiple soil types and not multiple fabric types. Similar to Pounds and Smalldon (1975a,b,c), dragging was the method of transference; but these new experiments were run under both wet and dry conditions.

In order to achieve reproducible and consistent results, the weighted fabric was not pushed by hand across the soil tray. This aspect of Pounds and Smalldon's method could not replicate a similar amount of force for every pass. Aware of this limitation, they experimented using greater and lesser force to ascertain whether this affected the number of fibres transferred. To maximise reproducibility of results in these current experiments, weighted fabric was dragged in timed runs across a soil tray using a drag-line.

Trace evidence on fabric and all bulk soil samples then underwent CAFSS stage 1 classification of soil morphology. Binocular and petrographic microscopy assisted to differentiate each sample and indicate provenance.

Image processing was programmed to analyse digital photographs taken *in situ* of trace soil transfer patterns on fabric. This was aimed to provide objective, quantifiable numerical data to assist or confirm the interpretation of soil transfer patterns as seen by the naked eye. The Trimble eCognition Developer software was also programmed to analyse Munsell Soil colour to identify and match trace soil on fabric to other trace soil evidence from the same location.

Pounds and Smalldon did not require an analysis of the colour of the wool fibres for their transference and persistence experiments (Pounds and Smalldon 1975b, 1975c, 1975a). They also did not have today's computer technology that enables a higher level of quantitative and objective results. But without their initial groundbreaking experiments, these soil transference experiments may never have come to pass.

1.4 Geology and natural soil of Royal Tasmanian Botanical Gardens, Queens Parade, Tasmania

Hobart is part of the Central Tasmanian Region, with a geological age ranging between the Late Carboniferous to Triassic. Landforms of the Central Tasmanian Region include mountain ranges, dissected plateaus, hills and ridges and undulating plains. Stratigraphy dates from Late Carboniferous to Early Permian sediments (including glacial); overlain unconformably by Permian shallow-marine and deltaic and Triassic lacustrine and fluvial sediments, including Permian and Triassic coal. Tertiary sediments and mafic volcanic are also present (Hergt *et al.* 1989).

The underlying geology of the Royal Tasmanian Botanical Gardens is primarily Jurassic dolerite except at the eastern boundary, where a layer of Triassic sandstone extends into the site.

With the breakup on Gondwana, large volumes of tholeiitic magma, estimated by Hergt *et al.* (1989) to be in the vicinity of 15,000km3, were intruded as dolerite sills in the mostly flat-lying Permo-Triassic rocks of the sedimentary Tasmania Basin. The magma had a basaltic andesite composition, probably formed from a 'primary' tholeiitic magma of similar composition to island arc and interarc basins, derived from a very depleted mantle source (Sun and Nesbitt 1978; Hergt *et al.* 1989). It is moderately enriched in SiO_2 relative to basalts, but slightly depleted in Fe, Mg and Ca and similarly rich in alkalis and P. These compositions can provide good soil fertility. Taking the form of a flattened cone, these doleritic intrusions covered an area of 30,000km^2 (Hergt *et al.* 1989); with limbs forming concordant sills (Leaman 1976).

As indicated in the soil map (Figure 1-1) derived mainly from the Australian Soil Resources Information System (ASRIS (Australian Soil Resources Information System) 2013), Hobart's dominant Australian Soil Classification soil orders (Isbell 2002) before white settlement cover the following soil orders: (i) Dermosols (green-shaded) in Queens Domain and Glebe, (ii) Sodosols (dark tan) in North and West Hobart, (iii) Chromosols (light tan in Hobart, South Hobart, Sandy Bay, Dynnyrne, Battery Point and Mount Stuart. Dermosols have structured B horizons and lack a strong texture contrast between the A and B horizons. Dermosols often have clay skins on ped faces. B2 horizons are often clayey, with free-iron oxide content less than 5% (McKenzie *et al.* 2004).

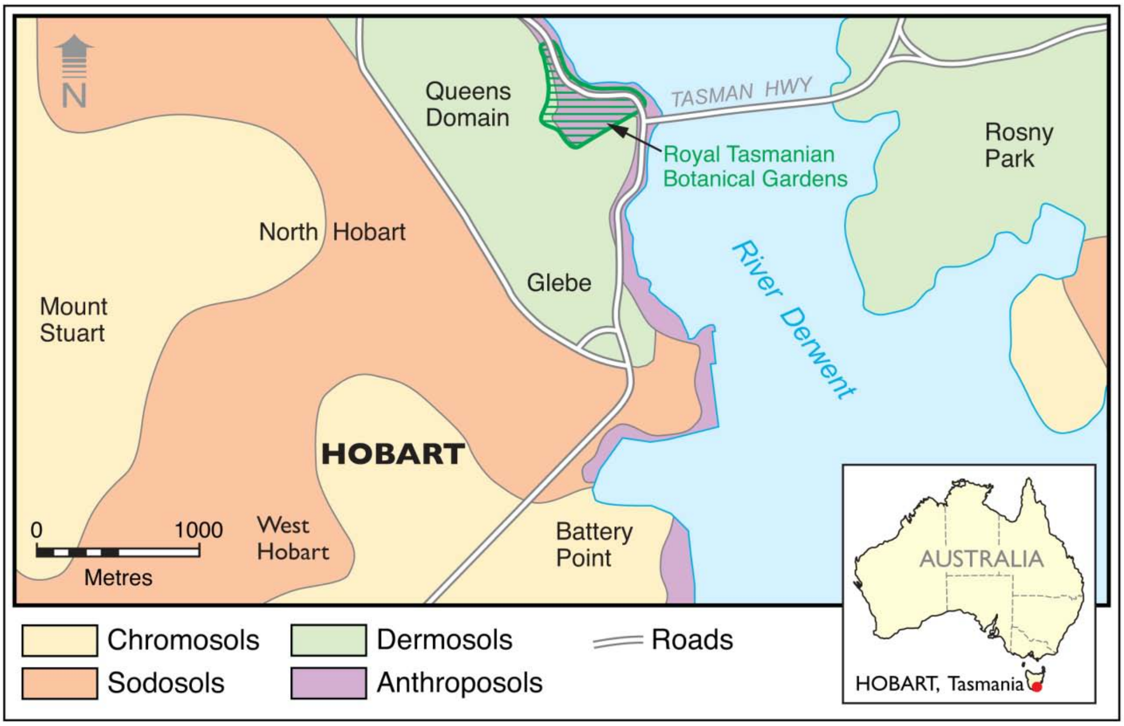


Figure 1-1 Soil map showing purple shaded Anthroposols, which dominate the Royal Tasmanian Botanical Gardens (green cross-hatched area) with minor Dermosols (Modified from ASRIS database) and inset showing the location of Hobart.

1.5 Human-made soils of Royal Tasmanian Botanical Gardens, Queens Parade, Tasmania

The natural Dermosols in the Royal Tasmanian Botanical Gardens (RTBG) in Queens Domain is generally a light clay over heavy black clay but most of the soil has been heavily modified by the introduction of sandy loam (Reid 2012). The majority of these grounds in the RTBG (green cross-hatched area) have been radically modified to create roads, walls, specialty gardens and smooth flat lawn surfaces. As a consequence, the dominant soils in the RTBG and on Hobart's waterfront as shown in Figure 1-1 (shaded a purple colour) comprise:

(i) Anthroposols in accordance with the Australian Soil Classification (Isbell 2002) or

(ii) Technosols in accordance with the World Reference Base (World_Reference_Base 2014) or

(iii) Human-altered and Human-transported material (HAHT) (Galbraith 2012) are defined in Chapter 3 of the 12th Ed. of the Keys to Soil Taxonomy (Soil Survey Staff 2014) and evidence of their existence is provided.

If humans levelled the land to produce terraces, creating artificial landforms, it will qualify as human-transported material. If humans altered the soil on purpose beyond standard agricultural practices (such as adding compost and gravel), it will qualify as human altered material.

All known information concerning the human-made changes to the soil in the RTBG and the human-transported soil, gravel and rocks imported in to transform these gardens was supplied by David Reid, Horticultural Coordinator of RTBG. The construction methods producing HAHT soils tested in STEs, as well as natural soils tested, are detailed in section 2.1.

2. FIELD AND LABORATORY METHODS

Summary

This section outlines the methods used to sample and analyse representative natural and human made soil samples from soil profiles.

2.1 Study area and materials

The diversity and heterogeneity of naturally occurring soils (eg. crystalline minerals, organic matter) and anthropogenic soils that often contain trace amounts of manufactured materials such as brick fragments and road gravel, enable forensic soil examiners to differentiate between soils.

The seven soil samples were sourced from the Royal Tasmanian Botanical Gardens (RTBG), Lower Domain Rd, Hobart, Tasmania, Australia (Figure 1-1). Five samples were anthropological (HAHT) soils (110.7.1, 110.5.1, 6.1, 8.1); including one brick sample (110.6.2). Six soils were sampled from between 0-10cm depth. At the natural soil site on the SE boundary, a horizon comprised of undecomposed leaf matter, was taken from 5-0cm above the soil surface (110.9.1). Underlying mineral soil (110.9.2) was also sampled at 0-10cm depth.

Sample site location coordinates were obtained using a GPS, using the WGS 84 Datum: Zone 54 South (Eastings and Northings). Photographs were taken of the soil profile sites and soil profiles. In the field, each soil profile was photographed with a scale and horizons were sub-sampled. Soil material was described and physical properties such as colour, consistency, structure and texture follow McDonald and Isbell (McDonald and Isbell 2009). Representative sub-samples were also collected in chip trays for: (i) soil morphological study/ description.

Table 2-1 Summary table of soil morphology and selected chemical properties

Locality	Sample no.	Matrix colour Dry	Moist	Texture	Gravel >2mm%	Quartz	Structure	Efferv. Class	Roots	WR	pH distill H20	pH CaCl2
Rose Garden Path	110.5.1	7.5YR 5/2 Brown	7.5YR 3/2 Dark brown	LS	90	R - S	Granular to single grain	NE	0	R	7.03	6.16
Rose Garden path near wall	110.6.1	7.5YR 5/2 Brown	7.5YR 3/2 Dark brown	S	90	R	Granular to single grain	NE	0	N	7.71	7.05
Brick fragments	110.6.2	2.5YR 7/8 Light red	2.5YR 5/8 Red	Brick	90	R - UT	Brick fragments & br. Dust	NE	0	N to R	N/A brick	N/A brick
Rose Garden bed	110.7.1	7.5YR 2.5/1 Black	10YR 2/1 Black	LS	15	R	Massive	NE	1	R	6.49	5.81
Japanese Garden	110.8.1	2.5YR 6/1 Reddish gray	2.5YR 3/1 Dark reddish gray	LS	90	R - A	Granular to single grain	NE	0	R	6.27	5.53
Natural soil (leaf litter)	110.9.1	leaves	leaves	Undecom-posed leaves	2	N/A	Undecom-posed leaves	NE	0	R	N/A leaves	N/A leaves
Natural Soil	110.9.2	7.5YR 2.5/2 Very dark brown	10YR 2/2 Very dark brown	LS	2	R - S	Massive	NE	0	R	6.86	6.54

Texture: S, Sand; LS, Loamy Sand; obtained by the “feel” method in accordance with McDonald and Isbell (McDonald and Isbell 2009).
Quartz = Quartz particles shape (Roundness and Sphericity): R = Rounded; S = Subrounded; UT = Subrounded tabular; A = Angular (McDonald and Isbell 2009).
Effervescence Class (H4) (Reaction to 6N HCl): NE = Non effervescent; (Schoeneberger *et al.* 2002).
Water Repellence (WR): N = Non water repellent; R = water repellent (McDonald and Isbell 2009).
Roots: 0 = None; 1 = few (1-10 fine roots) in sample area 100mm² (McDonald and Isbell, 2009; p.199).

Soil samples were sourced from three main sites at RTBG (Figure 2-1): the Rose Garden, bordered by a heritage-listed, convict-built brick wall (110.5.1 to 7.1), the Japanese Garden (110.8.1) and a natural soil site opposite the Japanese Garden by the Southern fence, Eastern section (110.9.1 and 9.2).

The textures of all soil samples are representative of the soil particles remaining after each sample was passed through a <2mm sieve. The loamy-sand texture recorded for soil from the Rose garden bed (110.7.1) is representative of the 10% very fine soil particles that remained after the >2mm quartz-rich gravel was removed.

Likewise, the loamy-sand texture of soil from the Rose garden path (110.5.1) is indicative of the texture of fine (<2mm) soil matrix, excluding the sandstone and quartz gravel making up 90% of this sample. The coarser sand texture of the fine (<2mm) particles of the same gravel path near the Eardley Wilmot brick wall, may indicate the presence of fine sand particles eroding off this 170 year old brick wall.

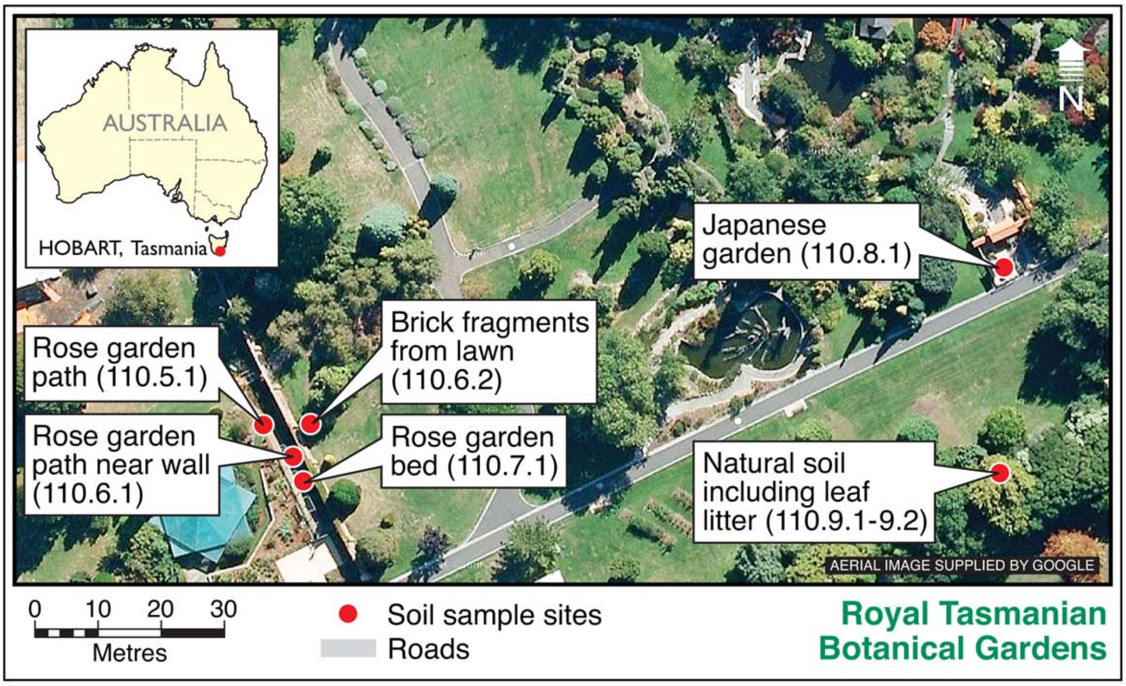


Figure 2-1 Map showing the distribution of seven soil samples used in STEs, taken from RTBG, Lower Domain Rd, Queens Domain, Hobart. (i) Rose Garden path (110.5.1 to 6.1); (ii) Lawn at base of Rose Garden Wall (110.6.2); (iii) Rose Garden bed (110.7.1) (iv) Japanese Garden (110.8.1); (v) Southern fence, Eastern section (110.9.1 to 9.2).

For the Rose Garden paths, the original natural soil was excavated and removed before adding 70-80mm of road base followed by a gravel surface layer 40-50mm thick (Reid 2012) (Figure 2-2 and Figure 2-3). The gravel is a mix of arkosic sandstone and andesitic-to-weathered mafic igneous rock.

Figure 2-2 Photograph of Rose Garden path (110.5.1) in RTBG. See also Figure 2-3 for soil on the Rose Garden path near the Eardley Wilmot brick wall (110.6.1).

The Rose Garden beds were constructed by excavating original soil to 300-400mm depth and backfilling with a mixture of 3 parts RTBG compost, 3 parts composted pine bark and 1 part coarse river sand (Reid 2012) (Figure 2-3).

Figure 2-3 Photograph of rose garden bed organic-rich soil covered with thick straw mulch (110.7.1) bordered by the Eardley Wilmot brick wall. Note also that sample 110.6.1 was taken from the Rose Garden path in close proximity to this wall.

The heritage-listed convict-built “Eardley Wilmot” brick wall running alongside the rose garden was constructed in 1843 from an unknown brick source (Reid 2012) (Figure 2-4).

Figure 2-4 Photograph of “Eardley Wilmot” brick wall running alongside the rose garden.

Because of its heritage listing, brick fragments could not be collected from the wall itself. Built in 1843, small brick fragments have continually eroded over the past 170 years. These small (0.5cm - 4cm) loose decomposing brick fragments, fossicked from the lawn area along the length of the wall, were collected to create the brick sample (110.6.2). Because these brick fragments were mostly half-buried in the lawn that runs alongside the wall (Figure 2-5), this sample also contained a small amount of natural soil that had coated some of the brick particles.

Figure 2-5 Photograph of “Eardley Wilmot” brick wall fragments (110.6.2) used for soil transfer experiments were fossicked from the lawn side of the wall. (See also Figure 2-1 and Figure 2-3 for views of the extensive lawn bordering one side of the wall).

The Japanese garden also had the original native soil removed. The area was then covered with compacted road base to a depth of 100mm depth before loose quartz-rich gravel was spread to 50mm depth (Reid 2012) (Figure 2-6). The quartz gravel is well-rounded to angular; appearing to come from several sources. A smaller percentage of the gravel is made from sub-rounded to angular dolerite, quartzite and iron-rich sandstone. In addition, the area also comprises a small quantity of ironstone gravel, which contains microscopic inclusions of quartz nodules.

Figure 2-6 Photograph of quartz-rich gravel soil surface of Japanese Garden at RTBG, with Director of RTBG and Prof Fitzpatrick.

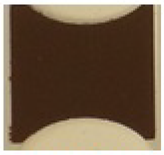
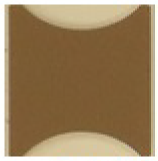
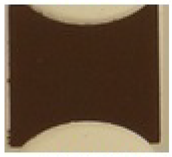
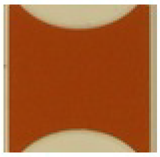
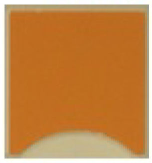
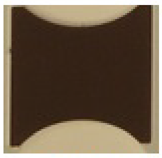
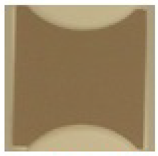
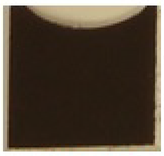
Two natural soil materials were collected from a soil profile under deciduous trees located on the south eastern boundary of the RTBG. The soil profile is covered by a thick layer of dry fallen leaves (sample 110.9.1), which overlies a dark organic-rich layer (sample 110.9.2) (Figure 2-7).

Figure 2-7 Photograph of natural soil under deciduous trees (110.9.1-2) near south eastern boundary of RTBG.

Detailed morphological descriptions of the seven soils sampled are provided in Table 2-1. The fine (<2mm) fraction of all soil samples (except the brick and undecomposed leaf samples) have either a sand or loamy-sand texture. Three of the HAHT or Technosol samples came from paths; with gravel >2mm making up 90% of the main constituents.

Munsell soil colour was recorded for the fine (<2mm) fraction of each colour in natural daylight (Table 2-1). From twenty-one soil samples initially tested from various locations throughout Tasmania, the colours registered for both dry and moist samples were later used in image processing (Table 2-2), to provide computer software with a basis for matching 'Red Green Blue' values with the standard Munsell soil colour scheme (Munsell Color Company 2009).

Table 2-2 Munsell colour of moist and dry fine (<2mm) fractions of soil samples. (Please refer to (Munsell Color Company 2009) for true colour of soil colour chips).

Soil sample Location	Munsell Fine <2mm (Moist) Fine (dry)	Munsell colour Fine <2mm (Moist) Fine (dry)	Moist	Dry
110.5.1 RTBG, Rose Garden path	**7.5YR 3/2** 7.5YR 5/2	**Dark brown** Brown	 **7.5YR 3/2**	 7.5YR 5/2
110.6.1 RTBG, Rose Garden path near brick wall	**7.5YR 3/2** 7.5YR 5/2	**Dark brown** Brown	 **7.5YR 3/2**	 7.5YR 5/2
110.6.2 RTBG, Brick fragments near wall	**2.5YR 5/8** 2.5YR 7/8	**Red** Light red	 **2.5YR 5/8**	 2.5YR 7/8
110.7.1 RTBG, Rose Garden bed	**10YR 2/1** 7.5YR 2.5/1	**Black** Black	 **10YR 2/1**	 7.5YR 2.5/1
110.8.1 RTBG, Japanese Garden	**2.5YR 3/1** 2.5YR 6/1	**Dark reddish gray** Reddish gray	 **2.5YR 3/1**	 2.5YR 6/1
110.9.1 RTBG, Natural soil site	LEAVES	N/A	N/A	N/A
110.9.2 RTBG, Natural soil site	**10YR 2/2** 7.5YR 2.5/2	**Very dark brown** Very dark brown	 **10YR 2/2**	 7.5YR 2.5/2

2.2 Laboratory soil analysis methods

The aim of this research was to visually identify patterns produced by the transfer method of dragging weighted clothing (specifically a bra) across a soil surface. Bulk soil samples underwent eighty-four (84) soil transference experiments (STE) in the lab, using both wet and dry sediment.

It was originally anticipated that XRD analysis would be heavily relied upon in order to decipher any soil transference patterns discovered. But when soil transfer patterns were being routinely identified and categorised by naked eye alone across all seven soil samples tested, knowing the exact mineral composition of the soil via XRD became a secondary consideration. Simple light microscopy and photomicrographs were also taken of all soil transfer patterns on fabric. However, digital photographs of STEs taken *in situ*, proved to be of greater scientific merit; creating a pristine record of the entire fabric surface of the STE. The apparent universality of these patterns produced six of the documented soil transference patterns with 100% consistency in natural soil, HAHT soil, a mix of HAHT and natural soil; even in a natural soil sample made entirely of undecomposed leaves.

2.3 Image processing computer analysis of digital photographs

Image processing computer analysis of digital photographs of trace soil patterns, taken in the laboratory immediately after each STE, provided numerical data of every soil transfer pattern produced on fabric. Despite the ease in which the human eye can identify these soil transfer patterns, image processing was undertaken to: (i) confirm patterns observed visually by human eye (ii) provide standardised numerical data of the colour and shape of soil objects >100 microns/2 pixels and (iii) allow statistical comparison of observed soil patterns. This included quantity and directionality of soil transferred, percentage of individual soil objects and aggregates and Munsell soil colour range. In a court of law, image processing analysis of trace soil evidence on fabric could be treated with the same respect as XRD analysis of a soil's mineralogy.

Image processing software from University of Tasmania's School of Earth Sciences provided an object-oriented image classification of soil patterns on fabric. Image processing was carried out using Trimble eCognition Developer software (version 8) to analyse digital photographs and classify objects transferred during soil transference experiments (STE) conducted in the laboratory at Mineral Resources Tasmania.

The images were RGB files with the red band analyses as Image layer 1, green as image layer 2 and blue as image layer 3. The classification was strongly dependent on colour both in raw measurements in each colour band and as colour ratios. Colour ratios were corrected for the gamma correction carried out by the camera.

The original digital photos were taken at a fixed distance above the 12.5cm diameter fabric round used in each soil transference experiment, under controlled artificial lighting conditions in the laboratory. During image preparation, non-relevant parts of the image were masked.

Often it is desirable to present orientation data to emphasise distribution of orientations independently of the geographic location of data. The types of diagrams most frequently used to present such information are histograms, rose diagrams and spherical projections (Allaby and Allaby 1999).

Using the image processing directional or orientation data, rose diagrams were applied to map the orientation of thousands of dry or moist soil particles displayed as≥2 pixels diameter transferred onto fabric. Rose diagram plots were created using GEOrient version 9.5.0 (Holcombe 2011) to provide a simplified computer image, illustrating the directionality of soil on fabric. Quantitative numerical data on directionality, produced by Trimble eCognition Developer software (version 8), were inputted into GEOrient. The resulting rose diagrams provided a quick and vivid method of comparing STE results from different soil samples.

2.4 Total carbon and sulfur

The carbon and sulfur content of the soil samples were determined using Nondispersive infrared (NDIR) analysis.

The carbon and sulfur contents of the soil samples were determined by Nondispersive infrared (NDIR) analysis using a Bruker G4 Icarus analyser, in the MRT laboratories, Rosny Park. The following standards were run during analyses to check calibration: AR4005 (C=1.42%, S=1.41%), AR4013 (C=2.93%, S=0.020%), AR4014 (C=5.87%, S=0.029%), AR4007 (C=7.27%, S=3.26%) and AR4024 (C=11.72%, S=0.418%).

2.5 Mineralogical analyses by x-ray diffraction

XRD analysis was undertaken to compare and contrast the mineralogy of the seven soils involved. If the soils used in the experiments were very similar in mineral composition, further STEs on soils vastly different in composition would be required before it could be concluded that soil transfer patterns documented in this paper were universal across all soil types.

Homogenous samples of each soil type (incorporating bulk and <2µm fractions) were hand ground to <20 microns in an agate mortar and pestle. The resulting fine powders were either gently back pressed into aluminium sample holders for X-ray diffraction analysis (XRD) analysis. XRD patterns of samples were collected with an automated Philips X-Ray diffractometer system: PW 1729 generator, PW 1050 goniometer and PW 1710 microprocessor with nickel-filtered copper radiation at 35kV/25mA, a graphite monochromator (PW1752), sample spinner and a proportional detector (sealed gas filled PW1711). The diffraction patterns were recorded in steps of 0.02° 2 theta with a standard scanning speed of 0.02 second counting time per step.

Analysis of the XRD patterns were performed using CSIRO XRD software: "VisualXRD", "PW1710 for Windows" and "XPLOT for Windows". Mineralogical phase identification were made by manually comparing the measured XRD patterns with a series of similarly-prepared standards of the more common minerals to enable some semi-quantitative analysis. Quartz, if present, is used as an internal standard. If quartz is not present, it is routinely added to the sample for a supplementary scan. The semi-quantitative results are calculated using single-peak calibration factors derived from scans of known mixtures of minerals. This follows the methods of Maniar and Cooke (Maniar and Cooke 1987) and Chung (Chung 1975); which are variants of the internal standard and matrix flushing method of Klug and Alexander (Klug and Alexander 1954).

2.6 Sports bra

The unpadded, underwire, sports bra used in all these experiment has three hook-and-eye back fasteners, underwires rising high between the cleavage, unpadded cups, and sliding shoulder-straps with metal buckles. The bra's fabric is nylon-elastane. A DD-cup size provided a large fabric area for experiments and the white fabric made it easier to locate and identify trace soil transferred.

2.7 Soil transference experiments to test the transfer method of dragging weighted clothing across soil surfaces

In order to identify patterns of soil transference created when weighted clothing (simulating a clothed human body) is dragged across a soil surface, an experiment was undertaken in the laboratory based on Pounds and Smalldon's (1975a,b,c) particle transfer experiments. Originally designed to test methods of transference and persistence of wool and acrylic fibres onto clothing, their method for fibre transference was adapted to transfer soil particles onto a bra.

Experimental design

A 2kg weight was enclosed in a plastic bag to enable easy cleaning between each STE. The side that was to be dragged across the soil bed was made as flat as possible, by cutting a plastic lid to the exact size and using duct tape to secure it to the weight. The drag line, made from packing tape, was wrapped firmly around the weight before also being secured by duct tape. The plastic bag was made firm and flat against the weight using duct tape also (Figure 2-8). A glass Pyrex 3 quart/2.8L dish was filled with a minimum of 3cm with bulk soil. This was placed on a non-slip mat, with heavy weights on one side to ensure the dish didn't move during the experiment.

Figure 2-8 Flat underside of 2kg weight, enclosed in plastic bag to enable easy cleaning between each STE. Weight placed in glass Pyrex dish used for all STEs, with yellow drag line kept low to maximise the 2kg weight's contact with the soil surface. Note non-slip mat under glass dish and heavy weights at front of the dish to ensure it doesn't move during the experiments.

The soil to be tested was then tipped into the glass dish and roughly made level, without compaction. The section of bra to be tested was then firmly attached to the weight, using a thick rubber-band (Figure 2-9). The sections of bra to be tested later were kept clean in a plastic cliplock bag. Each bra had the two cups and two shoulder-straps tested individually. As each test took place, the bra was photographed, microphotographed, and then placed in an individual cliplock bag, which was duct taped to minimise cross-contamination.

Figure 2-9 Bra cup is secured to 2kg weight using thick rubber-band. b) The remaining clean sections of bra are kept clean inside a cliplock bag on top. Note the bra is placed on clean paper whilst it is being attached to the weight, to avoid sediment being accidentally transferred to the fabric surface.

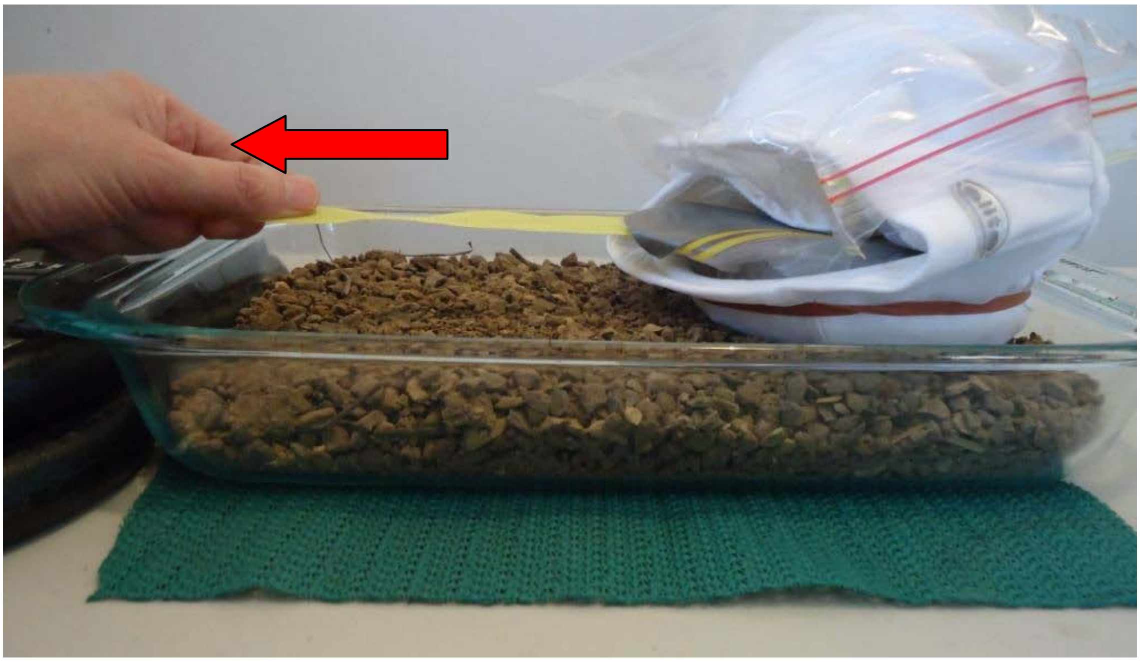
With a bra cup or shoulder-strap wrapped securely around the 2kg weight and the metronome set to 1 beat/second, the test run commenced. The weighted bra was gently placed at one end of the soil dish for a 3 second count, moved smoothly and continuously for 3 seconds to the other end of the soil dish and then left in place for 3 seconds (being lifted on the 3rd count) (Figure 2-10). The yellow drag line is kept low and parallel with the soil to ensure the weighted bra has constant and full contact with the soil surface.

The weighted bra was then gently turned right-side up, to maximise the quantity of soil particles remaining or persisting on the bra fabric in their original positions. The bra's target area was then photographed to document the trace soil patterns; before undergoing detailed microscopic analysis and photomicrography. Patterns resulting in the soil bed were also photographed.

The 2kg weight keeping the transferred sediment flat and stable was then removed and cleaned of soil with dry paper-towel. The bra was then placed flat in a labelled double-cliplock plastic bag. In the middle section of bra between the cups, the cliplock bag was taped on both sides with gaffer-tape. This prevented any loose sediment from either falling out of the bag or rolling into the middle section of the bra.

When dry bulk soil samples were first emptied into the glass dish, there were usually very fine clay-sized soil particles in the bottom of the bag that came out last; settling like fine 'dust' on the soil surface. This caused the first dry run of every new soil sample to consistently have more very fine soil transferred to bra fabric than in subsequent runs.

In summary, a smooth-surfaced 2kg weight with a diameter of 13cm/5", had either a bra-strap or cup secured with a red 10mm-thick rubber-band. This restricted potential movement or loosening of the strap/cup during the experiment; as well as simulating the effect of the weight of a human body on soil transfer patterns produced. Using a yellow 'drag line', each bra was then dragged in timed runs through a soil dish containing either wet or dry bulk soil. The drag line was kept parallel to ensure full contact of the weighted bra with the soil bed at all times.



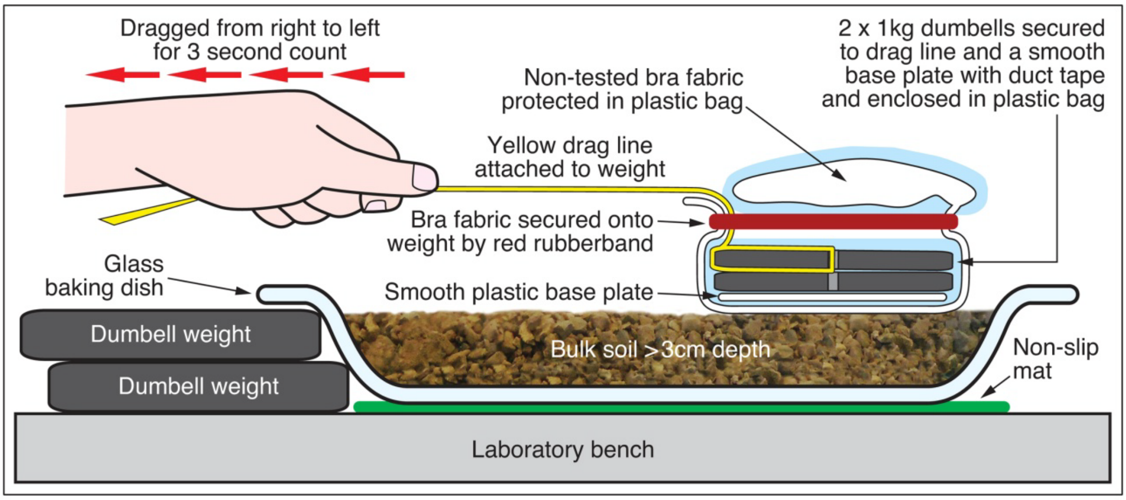


Figure 2-10 Photograph (above) and cross-section of weighted bra dragged from right to left over soil material during a three second count soil transference experiment. Sections of bra that are not subjected to being dragged over the soil during the experiment remain clean inside a cliplock plastic bag on top of the weight. Note the end of the glass Pyrex dish containing soil material and weighted bra is placed on a nonslip mat and a backstop of weights on the left to stop it moving during the transference experiment.

All bras were washed twice on a heavy-duty wash cycle, using 80ml of ‘Earth’s Choice’ liquid laundry detergent per wash, in a top-loading washing machine. Before the bras were washed, the washing machine was thoroughly cleaned. All filters were cleaned; in this case, the filters in each hose-fitting on both taps. The machine’s inside drum and central column were then cleaned with a sponge and hot water. In a final step to ensure the bras couldn’t pick up any sediment during the wash cycle, a cup of white vinegar was added to a hot water heavy-duty wash on a high-water setting, as recommended by a washing machine technician. Only then was the washing machine deemed clean enough for the bras to be washed.

The back-fasteners of each bra were joined together to prevent any hooks from snagging on and damaging another bra's fabric.

Bulk soil samples were air-dried before a small amount was sieved to separate a <2mm component for further analysis.

The brick sample (110.6.2) was placed in a clip-lock bag and roughly crushed with a geological hammer, to promote results consistent with the other soil samples collected. Particle size ranged from a fine powder to 1cm fragments.

The results of all STEs were photographed in situ with a Sony Cyber-shot DSC-W530 14.1 megapixel camera.

Low-powered binocular microscopy using a WILD Heerbrug M5-53707 microscope was undertaken on the seven control samples taken from the RTBG and on eighty-four (84) trace soil samples from 21 bras in the STEs. Digital photomicrographs were taken using the Leica DFC-425 and the Leica Application Suite, Version 3.6.0.

Every STE was individually photographed and photomicrographed whilst the 2kg weight holding the fabric flat remained in situ.

In preparation for the wet runs, soil in the dish was sprayed with distilled water until the soil colour changed evenly and water beaded. If the surface became dry and crusty between wet runs, the surface was jostled and rewetted.

Between each run, the soil surface would be gently levelled by hand without compacting the soil surface.

In the first test, a shoulder-strap was stretched tightly across the weight and secured. Each bra-strap was aligned with a yellow drag-line attached to the weight, to minimise fabric movement and ensure consistency of results with every run.

In the second test, a bra cup was stretched firmly and smoothly over the weight and secured. Every bra cup was positioned identically in proximity to the yellow drag-line, to keep results consistent regarding seam-lines and the cut of material. During each test, the yellow drag-line was kept low to the soil surface, ensuring the entire surface of the weight was kept in full contact with the soil.

The chosen section of bra was then dragged in timed runs through bulk soil samples. The right-hand (as if worn) bra cup and shoulder-strap underwent one dry run each and the left-hand bra cup and strap underwent one wet run each. In total, 84 soil transference experiments were run on 21 bras. Sections of bra not being tested were protected from accidental soil transfer in plastic clip-lock bags. Because bras were needed for future experiments, they couldn't be cut up.

3. MINERALOGY, CARBON AND SULFUR ANALYSES

Summary of mineral, carbon and sulfur analyses of all soil samples used in dragging STEs in the laboratory; to further investigate the universality of transference patterns across all soils.

3.1 Mineralogy

In order to ascertain how each soil's unique mineralogy (in particular clay), carbon and sulfur content affected subsequent soil transfer patterns, mineralogy, carbon and sulphur analyses were undertaken. Thirteen (13) minerals typical of loamy-to-clayey Tasmanian soils were identified.

The semi-quantitative determination of minerals in the whole soil by X-ray diffraction (XRD) is presented in Table 3-1. Quartz is the major mineral in these soils. Smectite is of secondary importance in the Rose garden and soil on the SE boundary. X-ray diffraction (XRD) diagrams are presented in Appendix 5.

Table 3-1 contains the results of XRD analysis of soil samples from the Royal Tasmanian Botanical Gardens that were prepared, examined and analysed The sample composed entirely of undecomposed leaf litter (110.9.1) was omitted from XRD analysis because it lacked any mineral content.

Table 3-1. Results of X-Ray Diffraction (XRD) analysis and organic carbon on soil samples from the Royal Tasmanian Botanical Gardens (approximate weight %)

Sample	110.5.1	110.6.1	110.6.2	110.7.1	110.8.1	110.9.2
Location	Rose Garden Path	Rose Garden Path near brick wall	Brick fragments from lawn area near brick wall	Rose Garden Bed	Japanese Garden	Natural Soil near SE boundary
Quartz	40±4	41±4	high Quartz content	69±5	83±5	32±3
Organic		2±1	possible amorphous material inorganic	24±2	5±1	38±2
Plagioclase	19±3	21±3	probable remains of inadequately-fired clays	3±1	4±1	7±2
Smectite	19±3	15±2	trace of Mullite	2±1	2±1	20±3
K-Feldspar	1±0.5	2±1		2±1	1±0.5	3±1
Halloysite	3±1	2±1	Calcite and Rutile			
Clinopyroxene	3±1	2±1			3±1	
Mica					1±0.5	
Hematite	8±2	9±2	Hematite			
Ilmenite	1±0.5	2±1				
Laumontite	4±1	4±1				
Kaolinite					2±1	
Stilbite	1±0.5	1±0.5				
Apatite	1±0.5	1±0.5				

A range of results was given for each mineral detected, to compensate for a possible 'peak overlap' that may interfere with identifications and quantitative calculations; such as can occur between Potassium Feldspar and Clinopyroxene.

Amorphous material and trace amounts of minerals not detected are shown as blanks.

3.2 Organic carbon and sulfur

Table 3-2 contains the results of NDIR analysis of soils undertaken at MRT. Organic content of soil samples was calculated using NDIR measurements. No sulphur-containing minerals were identified in any sample. Due to its lack of mineral content, the soil sample composed entirely of undecomposed leaf litter (110.9.1) was omitted from NDIR analysis.

The Carbon contents were converted to approximate Total organic matter, by multiplying the total organic carbon content by 1.7, a standard figure (Howard, 1965).

Small Sulfur contents were noted in most samples but no Sulfur-bearing species were identified; appearing to correlate with organic matter.

Table 3-2. Nondispersive Infrared Analysis (NDIR) of Carbon and Sulfur Content of soils from the Royal Tasmanian Botanical Gardens.

Sample	Location	Carbon (%)	Sulfur (%)	Analyses
110.5.1	**Rose Garden Path**	0.70	0.09	2
110.6.1	**Rose Garden Path near wall**	1.21	0.08	2
110.6.2	**Brick fragments from lawn area near brick wall**	0.29	0.06	2
110.7.1	**Rose Garden bed**	14.0	0.33	4
110.8.1	**Japanese Garden**	3.10	0.12	3
110.9.2	**Natural soil near SE boundary**	22.8	0.54	3

Standards run during analyses to check calibration: AR4005 (C=1.42%, S=1.41%), AR4013 (C=2.93%, S=0.020%), AR4014 (C=5.87%, S=0.029%), AR4007 (C=7.27%, S=3.26%) and AR4024 (C=11.72%, S=0.418%)

4. CLASSIFICATION OF SOIL MATERIALS

Summary

This section summarizes the classification of all soil materials used in the laboratory dragging experiments in accordance with The World Reference Base (WRB) and Australian Soil Classification (ASC).

Sufficient descriptive, chemical and mineralogical (XRD) data was acquired on the 7 soil samples collected to characterise properties and classify the soil materials. Based on soil morphology (Table 2-1) and mineralogical data (Table 3-1), classification of the 7 soil materials was made according to The World Reference Base for soil resources (World_Reference_Base 2014) and the Australian Soil Classification (Isbell 2002). The classification of each soil material is presented.

The soil morphological descriptors of five soil materials and mineralogical data indicate two distinct groups, which are reflected in their soil classification as indicated in Table 4-1. These two groups of soil materials classify as: (i) natural soil materials or (ii) artefacts[1] or artefact materials (i.e. created or substantially modified by humans as part of an industrial or artisanal manufacturing process to manufacture “roads” e.g. road metal) and classify as Anthroposols or “man made materials” [Urbic Technosols (Ekranic-like)] or Spolic Technosol materials (World_Reference_Base 2014) or Anthroposol materials (Isbell 2002).

Summary description of Technosols (World_Reference_Base 2014): Connotation: Soils dominated or strongly influenced by human-made material; from Greek technikos, skilfully made.

[1]Artefacts Definition (World_Reference_Base 2014): Artefacts (from Latin ars, art, and facere, to make) are solid or liquid substances that are:

1. one or both of the following:
   a. created or substantially modified by humans as part of an industrial or artisanal manufacturing process; ***or***
   b. brought to the surface by human activity from a depth where they were not influenced by surface processes, with properties substantially different from the environment where they are placed; ***and***
2. have substantially the same properties as when first manufactured, modified or excavated.

Technosols Definition (World_Reference_Base 2014):Other soils having :

- 20 percent or more (by volume, by weighted average) artefacts in the upper 100 cm from the soil surface or to continuous rock or a cemented or indurated layer, whichever is shallower; or
- a continuous, very slowly permeable to impermeable, constructed geomembrane of any thickness starting within 100 cm of the soil surface; or
- technic hard rock starting within 5 cm of the soil surface and covering 95 percent or more of the horizontal extent of the soil.

Human-transported material and human-altered material are defined in Chapter 3 of the 12th Ed. of the Keys to Soil Taxonomy, and evidence of their existence provided (Soil Survey Staff 2014). If humans levelled the land to produce terraces, creating artificial landforms, it will qualify as human-transported material. If humans altered the soil on purpose beyond standard agricultural practices (such as adding lime), it may qualify as human altered material.

Table 4-1. Soil type and morphology, Australian Soil Classification of soil materials (Isbell 2002) and the approximate corresponding World Reference Base for Soil resources class (World_Reference_Base 2014).

Locality (Depth cm)	CAFSS Code1[1,2]	[3]Munsell Soil Colour Fine <2mm (moist) (dry)	Soil type[4]	Brief Description	The Australian Soil Classification (Isbell 1996)	The World Reference Base for soil resources (WRB) (WRB;
Rose garden path (0-10cm)	110.5.1 Rose-path-Anth	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	Anthropogenic gravelly sandy loam soil	Gravel (90%; arkosic sandstone and andesitic-to-weathered mafic igneous rock) loamy sand, water repellent, 0.7% Carbon (C).	Spolic Anthroposol; very gravelly, sandy, very shallow	[5]Spolic Technosol (Densic)
Rose garden path near wall (0-10)	110.6.1 Rose-path-wall Anth	**Dark brown 7.5YR 3/2** Brown 7.5YR 5/2	Anthropogenic gravelly sandy loam soil	Gravel (90%; as above)), sand, non water repellent, 5% brick fragments, 1.2% C.	Spolic Anthroposol; very gravelly, sandy, very shallow	[5]Spolic Technosol (Densic, Transportic)
Brick fragments (0-2)	110.6.2 Brick-Anth	**Red 2.5YR 5/8** Light red 2.5YR 7/8	Anthropogenic brick fragment-rich soil	Gravel (90%), sandy, water repellent, weathered brick fragments (0.5-4 cm) ,1.2% C.	Urbic Anthroposol; very gravelly, sandy, very shallow	[5]Urbic Ekranic Technosol (Transportic)
Rose garden bed (0-10)	110.7.1 Rose-bed-Anth	**Black 10YR 2/1** Black 7.5YR 2.5/1	Anthropogenic, organic-rich sandy loam soil	Gravel (15% coarse river sand), loamy sand (25%) , water repellent, 30% fine compost, 30% composted pine bark, 14 % C.	Hortic Anthroposol; non-gravelly, sandy, shallow	[6]Hortic Anthrosol (Escalic)
Japanese garden bed (0-10)	110.8.1 Japan-bed-Anth	**Dark reddish gray 2.5YR 3/1** Reddish gray 2.5YR 6/1	Anthropogenic, quartz-rich, gravelly, sandy soil	Gravel (90%: ~80% rounded quartz, 10% sub-rounded to angular dolerite;5% ironstone), loamy sand, water repellent, 3 % C.	Spolic Anthroposol; very gravelly, sandy, very shallow	[5]Spolic Technosol (Grossartefactic, Transportic)
South eastern boundary (5-0) (0-10)	110.9.1 Sth-E-bound-Nat 110.9.2	**Very dark brown 10YR 2/2** Very dark brown 7.5YR 2.5/2	Natural organic-rich soil Natural loamy soil	Undecomposed Leaves (60%) and decomposed (40%) Gravel (2%), loamy sand, water repellent, 23 % C.	Humose, Mesotrophic, Brown Dermosol; non-gravelly, sandy, deep	[7]Eutric Cambisol (Humic)

Where: [1]Anth: Anthroposol (Isbell 2002); [2]Nat: Natural soil; [3]Munsell Soil Colour: measured on the fine earth fraction (<2mm);

[4] Special-purpose technical soil classification system, which uses plain English language places strong emphasis on being either an Anthropogenic soil or Natural soil, soil texture (e.g. gravelly, sandy, sandy loam) and presence of high amounts of organic carbon (>10%; organic-rich)

[5]Classification of Technosols (World_Reference_Base 2014): Connotation: Soils dominated or strongly influenced by human-made material; from Greek *technikos*, skilfully made. They contain a significant amount of *artefacts*.

[6]Classification of Anthrosol (World_Reference_Base 2014): Connotation: Soils with prominent characteristics that result from human activities; from Greek *anthropos*, human being (e.g. such as addition of organic material and cultivation).

[7]Classification of natural soils : Connotation: Soils with substantial soil formation such as Dermosols (Isbell 2002) or Cambisols (World_Reference_Base 2014)

5. RESULTS OF SOIL TRANSFERENCE EXPERIMENTS (STE)

Summary
This section presents the results of 84 soil transference experiments.

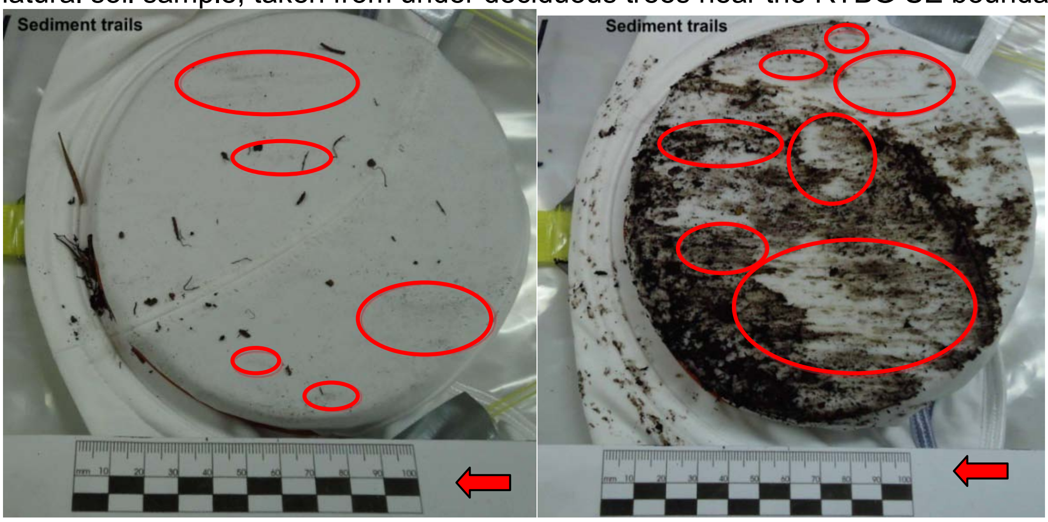
5.1 The transfer and persistence of both anthropogenic/HAHT and natural soil samples onto a nylon/elastane bra; through the transfer method of dragging weighted clothing across a soil surface

Image processing numerical data quantifying the quantity of soil transferred to bra cup fabric, the percentage of individual soil objects and aggregates, the range of Munsell soil colours detected and Rose diagrams displaying directionality of soil transferred is discussed in depth in the image processing sections of this paper.

5.1.1 Soil 'trails' on bra cups and bra straps

Soil 'trails' on the fabric, evidence of the transportation of soil parallel to the direction of movement, could be seen with the naked eye on all dry and wet soil runs in every sample. First recognised during the wet runs due to the darker colour and higher quantity of wet soil transferred, soil 'trails' stood out strongly against the white colour of the bra. A closer visual examination of the dry runs (sometimes requiring light microscopy), confirmed the same patterns.

Note that the two bra cups shown in Figure 5-1 are displayed smaller than actual size; and yet soil trails can still be identified. These STEs were produced from the same natural soil sample, taken from under deciduous trees near the RTBG SE boundary.



a) DRY RUN b) WET RUN

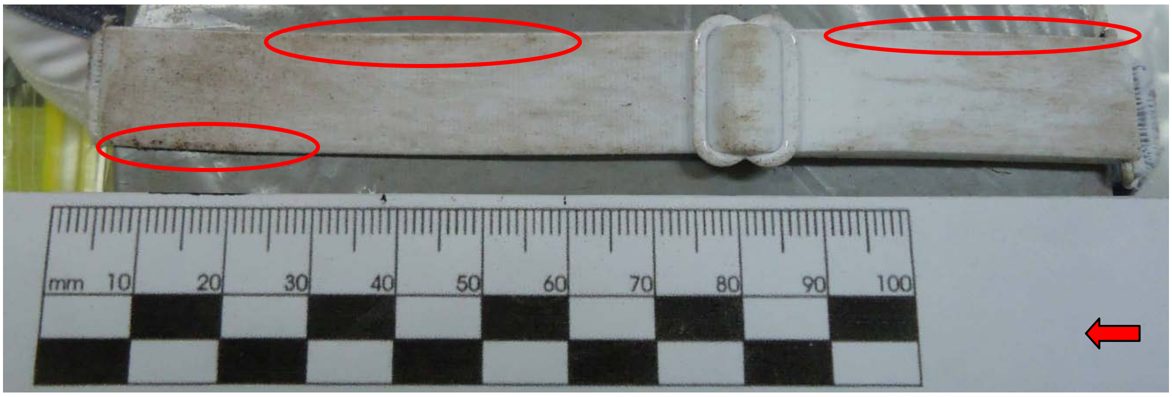
Figure 5-1 Soil trails on fabric, aligned with direction of movement right to left. The dramatic difference that can occur when soil from the same soil sample is transferred during a dry soil run (a) and wet soil run (b) is shown using natural soil sample (110.9.2). Notice also the massive build-up of soil over the raised middle seam and the minimal amount of soil transferred directly behind it.

Another example of this transportation of soil is seen in HAHT soil sample from the Rose Garden path (Figure 5-2). During a wet soil run, a muddy fragment (<2mm) has been transported over the metal buckle (confirmed by the soil trail left behind it on the buckle-bar). It is persisting on the very edge of this buckle-bar; and from the shadow cast, is not touching the fabric underneath for support.

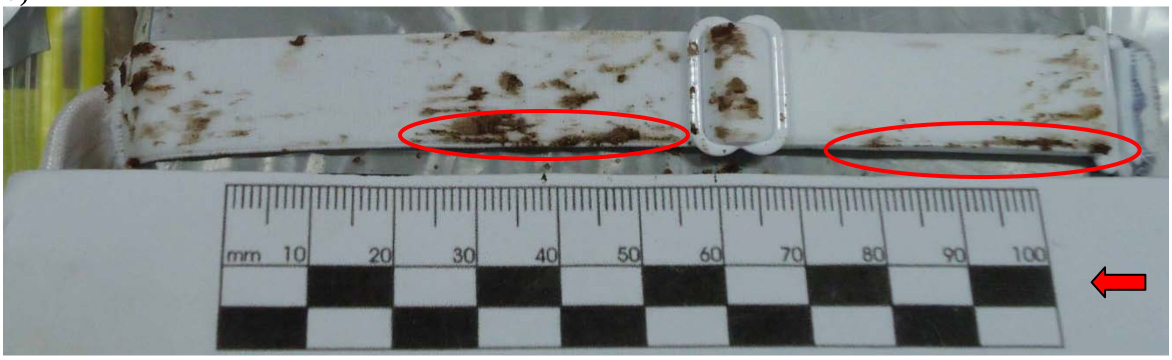
Figure 5-2 Photomicrograph of muddy fragments from a STE wet run using HAHT soil sample (110.5.1) from the Rose Garden path. Note the soil trails coming over the fabric on top of the buckle (Microscope magnification = 6X). Direction of movement = up.

5.1.2 Areas of soil accumulation on bra-straps after weighted fabric was dragged across a soil surface

Soil also accumulated intermittently along one or both fabric edges of all shoulder-straps in both wet and dry soil runs (Figure 5-3). This provided evidence not only that the fabric was dragged, but that the direction of movement was parallel to the bra-strap during transfer.



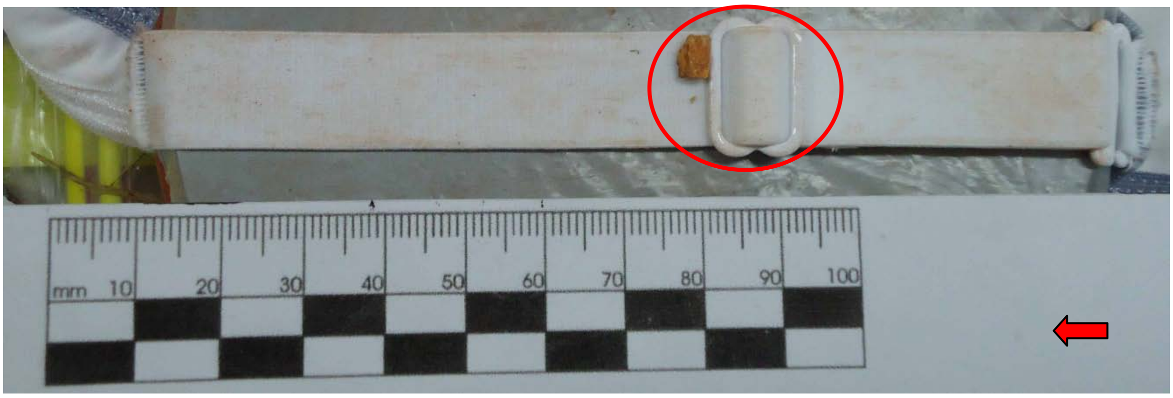
a)



b)

Figure 5-3 Soil accumulation along the edges of bra-straps in HAHT soil sample (110.5.1) from the Rose garden path (Direction of movement = right to left). In dry run a) note the fine (1mm) elongated aligned fragment on the bra-strap above the 50mm mark on the scale-bar. Fine soil trails are also evident near the 100mm mark. In wet run of the same sample (110.5.1) b), the soil trails are much more evident.

On the bra-strap, one of the best areas to differentiate not only dragging as the method of transfer, but also soil trails indicating direction of movement, was the fabric crossing over the metal buckle; as well as soil distribution around the buckle itself. As shown in brick fragment sample (110.6.2) (Figure 5-4), the accumulation of soil in front of the leading edge of the buckle in all samples indicated it was scraping and collecting soil onto the fabric in front. This pattern strongly indicated not only that the fabric was dragged across soil, but also the direction of movement.



a)

b)

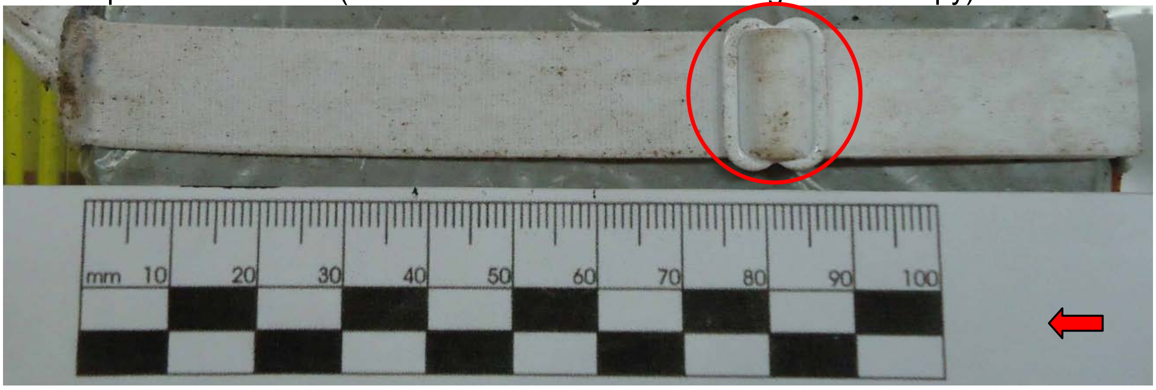
Figure 5-4 Using brick fragments from near the brick wall (110.6.2), soil trails over fabric in middle of buckle and accumulation of soil on the bra-strap fabric in front of the metal buckle in both dry (a) and wet (b) runs. Note the large brick fragment (4mmx5mm) that persisted on the fabric in dry run (a) even when the weight was turned upright; and the lack of soil on fabric behind the buckle in both examples. Note also the distinct soil trails across the fabric in the middle of the buckle in wet run b). (Direction of movement = right to left).

This observation was also confirmed from soil patterns left in the soil bed after every STE. There was a marked difference in the pattern of transfer left in the soil bed when a bra-cup or a strap was tested. When a bra-cup was dragged over a soil surface, it tended to drag a large amount of soil to the left side of the soil dish (Figure 5-5). However, when a bra-strap was tested, the metal bars of the raised bra-buckle caused a deeper and more distinct pattern to emerge in the soil bed than did the smooth, wide and flat expanse of bra-cup. The metal buckle protruding from the raised section of strap appeared to have ploughed into the soil surface due to the weight above; in a pattern aligned with the direction of drag. In Figure 5-5 b), the deep gouging out of soil stops exactly where the metal buckle has come to rest in the soil dish. To the left of this, the narrow shape of the strap is clearly visible.

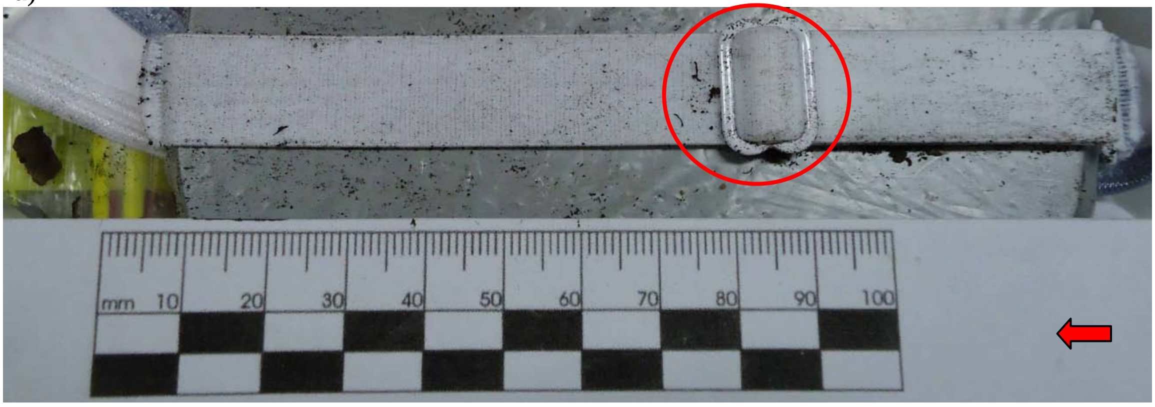
Figure 5-5 Drag patterns left on the soil surface of HAHT soil sample from the Rose Garden path (110.5.1) after a STE, testing the transfer method of drag on dry soil, has been run. In a), a weighted bra cup has pushed the soil surface up to one end of the tray in the direction of movement (right to left). In b) a weighted bra-strap has carved a narrow line through the soil surface, leaving the remainder of sample generally level in the dish (see line of soil surface at top of photo).

5.1.3 'Dusting' of very fine soil particles on metal buckles when very dry soil samples were tested

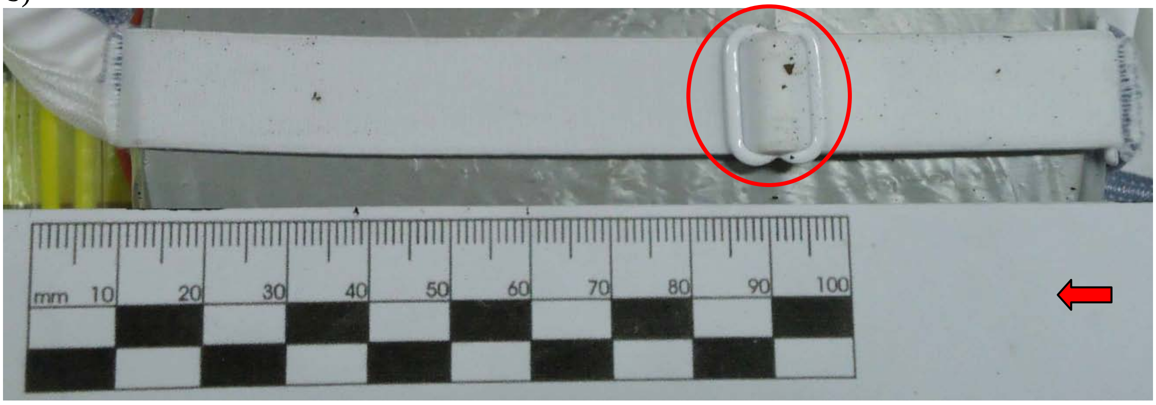
In all 21 dry soil runs using a weighted bra-strap in all seven soil samples, a 'dusting' of fine clay-sized particles would be deposited evenly over the entire metal buckle (Figure 5-6). This 'speckling' only occurred when soil was dry. Digital photos reveal this fine transfer pattern can be seen by naked eye. The STE result from natural soil (110.9.1) is included (Figure 5-6 c) to show that even in a sample made entirely of leaves, this transfer pattern is evident (albeit harder to identify without light microscopy).



a)



b)



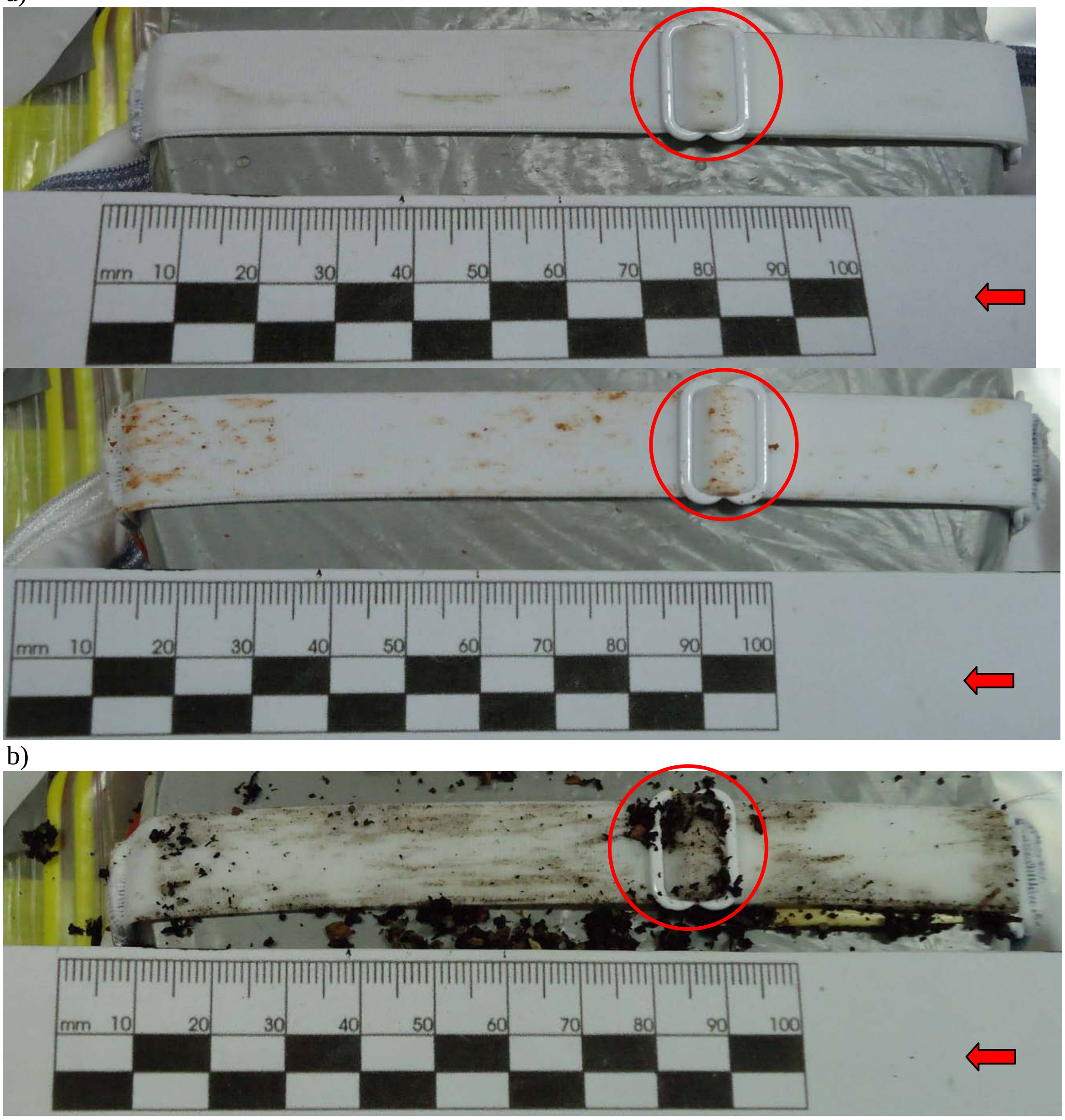
c)

Figure 5-6 'Dusting' of fine clay-sized particles that were transferred evenly over the metal buckle in all 42 STE dry runs in all seven soil samples tested. Dry run a) is from HAHT soil sample from the Rose Garden Path near the brick wall (110.6.1). Dry run b) is from natural soil sample from the SE fence (110.9.2). Dry run c) is from natural soil sample composed entirely of undecomposed leaves (110.9.1). (Direction of movement = right to left).

5.1.4 Very moist soil left metal buckles shiny with small soil aggregates or microscopic trace soil in water droplets

In all 21 wet soil runs dragging a weighted bra-strap across seven different soils, trace soil was transferred to the metal buckles in small to microscopic amounts. After dragging through moist soil, all buckles appeared shiny clean by naked eye; except for a few 1-2mm muddy clumps persisting on five of the seven soils tested (Figure 5-7). This contrasted with dry soil runs, where the speckled surface produced an all-over matt appearance on the metal buckle.

a)



c)

Figure 5-7 Metal buckle is mostly shiny clean, except for 1-2mm muddy clumps of soil. Wet run a) is from HAHT soil sample from the Japanese Garden path (110.8.1). Wet run b) is from HAHT brick fragments from lawn bordering the heritage-listed brick wall (110.6.2). Wet run c) is a mixture of HAHT and natural soils from the Rose Garden Bed (110.7.1). Note that areas without clumps of soil are shiny clean and do not have an evenly fine dusting of soil covering them. (Direction of movement = right to left).

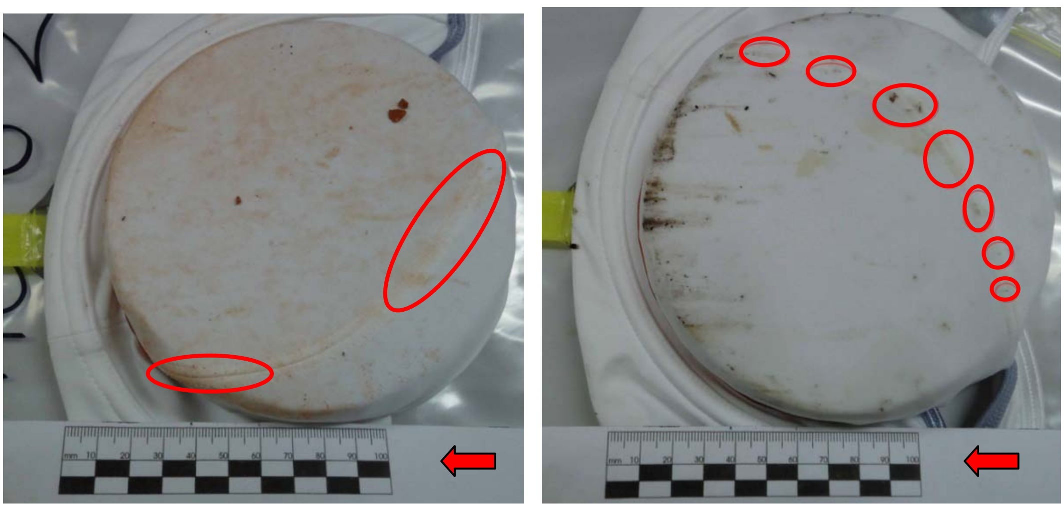
Two soils tested had negligible clay content, namely anthroposol Japanese garden soil consisting of 90% gravel and the top horizon of natural soil on SE boundary consisting of undecomposed leaves (Table 3-1). Metal bra-strap buckles dragged across these two moist soils appeared by naked eye as shiny clean and devoid of any trace soil transferred. However using light microscopy, water droplets on the otherwise clean buckles contained extremely fine soil particles (Figure 5-8). These two soil transfer patterns only occurred when soil was wet.

(a) MOIST Japanese Garden soil (110.8.1) **(b) MOIST SE boundary natural soil (110.9.1)**

Figure 5-8 Photomicrographs of trace soil patterns using the transfer method of dragging weighted fabric for a three second count across a soil bed containing moist soil. The only soil persisting on the metal buckles is contained in water droplets.

5.1.5 Soil accumulates in front and on top of raised seams in both wet and dry soils

In all 42 STEs using either wet or dry soil, soil accumulated in front and on top of raised middle seams in all bra cups. It was also noted that soil was minimal directly behind the raised seam; indicating that the seam was at an angle to the direction of motion (Figure 5-9. Also refer back to Figure 5-1). Even with minimal soil transferred from undecomposed leaf litter (110.9.1), very fine soil has still been transferred onto this raised middle seam.

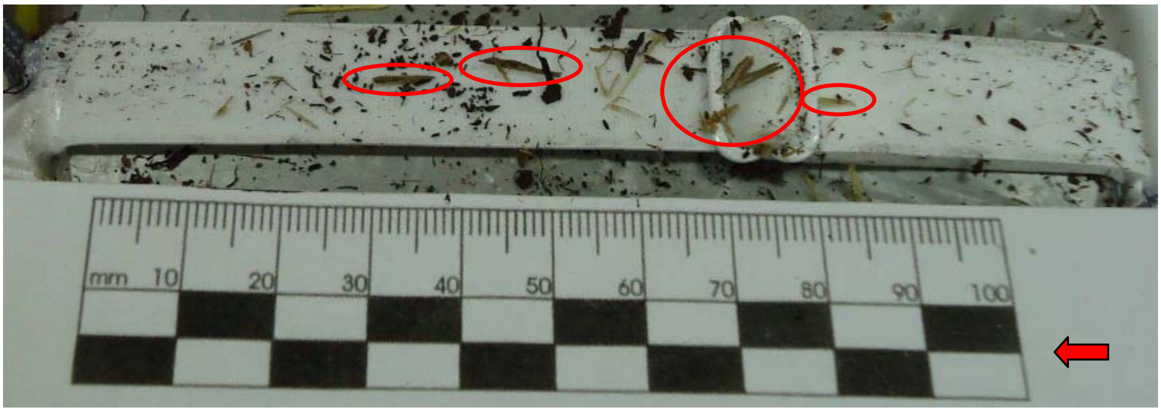


a) b)

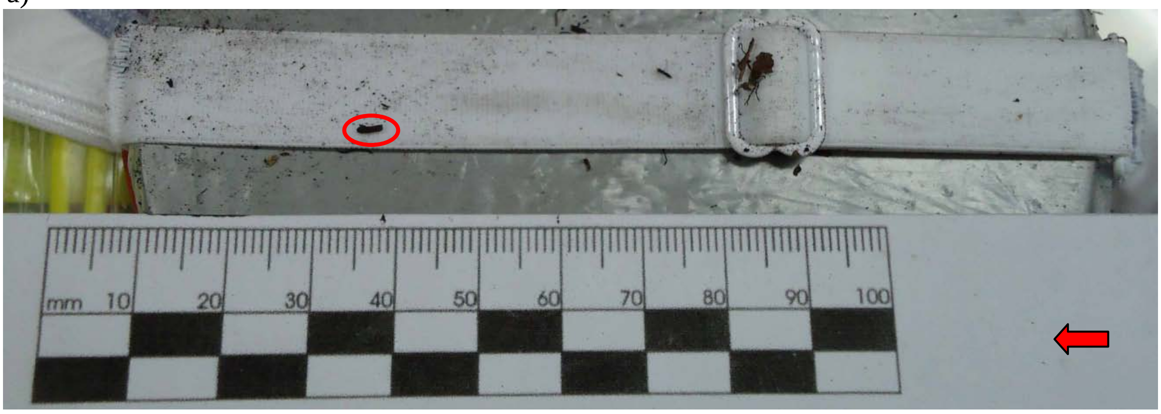
Figure 5-9 Soil accumulates in front of and on top of the raised middle seam of the bra-cup. In dry run a) taken from HAHT brick fragments (110.6.2), there is not only soil accumulating in front of and on top of the raised seam, but a definite change in colour behind the seam; due to the lack of soil transferred directly behind it. In wet run b) taken from natural soil sample made entirely of undecomposed leaves (110.9.1), very fine soil still accumulates in small patches on the raised seam. Notice also the striking soil trails aligned with the direction of movement, near the western edge of the bra cup. As in Figure 9b, there is more soil/mm in front of this raised seam than behind it. (Direction of movement = right to left).

5.1.6 Elongated particles of soil align on the fabric parallel with the direction of movement

Elongated particles of soil (such as grass seeds, dry grass and wood debris ≥2mm), aligned parallel with the direction of movement. Although all seven soil samples produced this pattern, it only occurred in approximately 65% of STEs (Figure 5-10 and Appendix 1). This transfer pattern proved a much less reliable visual method to establish the direction of movement than the more persistent and very distinctive soil trails; and was inconsistently produced amongst the elongate particles transferred to fabric. Outside of a controlled laboratory environment, this pattern could not be relied upon to infer that a victim had been dragged, unless elongate soil particles, such as grass seeds or twigs were actually embedded or pushed under the fabric.



a)



b)

Figure 5-10 Elongated particles of soil aligned parallel with the direction of movement (right to left). In dry run a) from the mix of HAHT and natural soil from the Rose Garden bed (110.7.1), elongated organic particles on top of the buckle and on both sides of the strap, have aligned with the direction of movement. However, there are still many elongated particles that have not aligned. In dry run b) from natural soil near the SE fence (110.9.2), several elongated particles have aligned along the bra-strap (but not on the buckle) in the direction of movement. Notice also the soil trails on both sides of this strap.

In Figure 5-11, elongated soil particles (3-5mm dry grass and wood fibres) from dry Rose Garden bed soil (110.7.1) are persisting on the fluffy seam at the back end of the strap. They are clearly aligned with the direction of movement, from right to left. Note the faint sediment trails running along the entire strap length; whilst the majority of loose particles are persisting on the strap in front of the metal buckle.

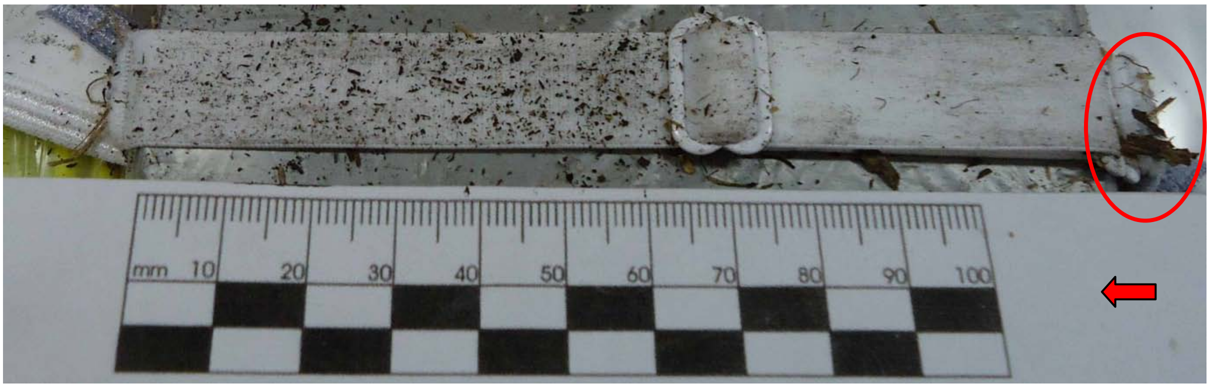


Figure 5-11 STE dry run using the soil sample from the Rose Garden bed (110.7.1); which is a mixture of natural and HAHT soil. (Direction of movement = right to left).

5.1.7 The persistence of fine trace soil transferred by dragging synthetic nylon-elastane fabric across a soil surface

Evidence of the delicate and transitory nature of loose particles of trace soil on fabric was documented in the laboratory. Light-weight organic elongated particles (fine roots between 1mm-2mm in length) could be blown out of their original position on fabric by air-conditioning within seconds. This was less of a problem with smaller or heavier elongated particles. But in the field, wind and rain (notwithstanding the body being moved or clothing removed), could degrade the pristine record that trace soil patterns can provide forensic investigations. Rose garden bed soil (110.7.1) contained many fine roots and other elongated organic particles. When the bra was removed from the 2kg weight, simulating clothing being removed from a female victim, static electricity produced by the nylon-elastane fabric being dragged for 3 seconds through the soil dish (over 20 minutes earlier), caused light-weight organic elongated particles to stand up on end and even shoot off at great speed (Figure 5-12).

Figure 5-12 After a STE dry run using Rose Garden bed soil (110.7.1), elongate fragments stand up on end due to static electricity after the nylon-elastane fabric of the bra has been dragged for three seconds across the soil surface.

5.1.8 Fluffy-textured raised seam accumulates trace soil at ends of bra-straps

The fluffy raised seam at the top and bottom of the bra-strap could accumulate soil in both wet and dry soil runs (Figure 5-13). It was anticipated that this fluffy surface would collect more soil that the finely-woven bra strap. But this hypothesis was proven inconclusive by the STE results. This transfer pattern was the least reliable; only occurring in 47.6% of dry runs and 28.6% of wet runs on average over all seven samples (Appendix 1).

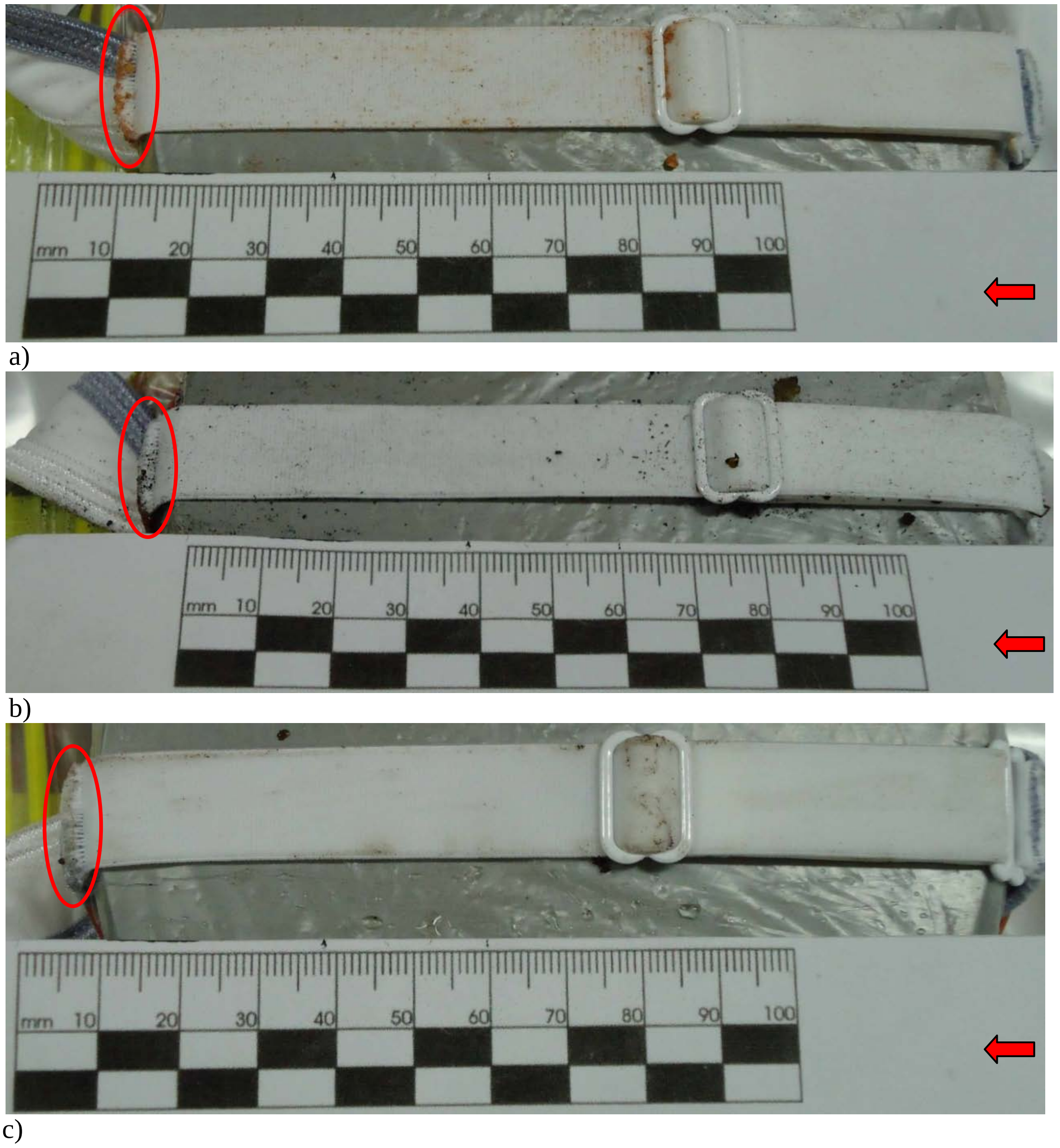


Figure 5-13 Soil accumulating in the fluffy seam at the front of the bra strap. Dry run a) is taken from HAHT brick sample (110.6.2). Note also the accumulation of soil in front of the buckle. Dry run b) is taken from natural soil (110.9.2). Wet run c) is taken from natural soil made up of undecomposed leaves (110.9.1). Even in a sample with minimal soil transference, familiar patterns indicating the transfer method of drag are still evident: a build-up of soil over the buckle fabric in fine soil trails and also intermittently along both strap edges. (Direction of movement = right to left).

In summary, eight transfer patterns were seen across all seven soils tested; but only the first six occurred with 100% consistency (Appendix 1).

(1) Soil ‘trails’ were observed by naked eye on the bra-straps and cups as a result of soil transported across the fabric parallel to the direction of movement. The darker colour of wet soil contrasted more strongly against the white fabric compared to dry soil; and a greater quantity of wet soil was transferred than dry.
(2) Soil accumulated intermittently along the edges of shoulder-straps in all STEs. This indicated not only that fabric was dragged, but that direction of movement was parallel to the bra-strap during transfer.
(3) Soil objects accumulated in front and on top of raised middle seams in all bra cups, at an angle to the direction of motion; regardless of soil moisture content. Soil transference was minimal directly behind the raised seam; indicating direction of movement.
(4) Likewise, soil accumulated on the metal bra-strap buckle and on strap fabric in front of the leading edge of the metal bra-strap buckle, when the strap was dragged across soil. This provided an indicator of direction. This soil could be seen by naked eye alone, except when moist soil had minimal clay content; as occurred with 90% quartz gravel (Japan-bed-Anth) and natural soil composed of undecomposed leaves (Sth-E-bound-Nat-leaves). These exceptions are discussed in greater detail in pattern (6) below.
(5) When the weighted bra was dragged across dry soil, very dry clay-sized particles ‘dusted’ or speckled the metal bra-strap buckle evenly like icing sugar.
(6) Moist soil left metal bra-strap buckles wet and shiny, often with 1-2mm muddy clumps transferred onto an otherwise shiny clean surface; to an extent dependent on soil type. This contrasted with dry soil runs, where the speckled surface produced an all-over matt appearance on the metal buckle. Occasionally, these tiny clumps had their own microscopic soil ‘trails’. Metal buckles dragged through soil with negligible clay-sized content (Japan-bed-Anth and Sth-E-bound-Nat-leaves) appeared shiny clean with a few water droplets remaining. However, using light microscopy, water droplets were clouded with extremely fine soil particles.
(7) Regardless of moisture content, elongated particles of soil material such as grass seeds, dry grass or wood debris≥2mm), aligned parallel with dire ction of movement. This pattern was not consistent throughout all STEs, occurring on average 65% using seven soils tested.
(8) Soil accumulated in fluffy raised seams at the ends of bra straps. This occurred in only 47% of dry soil STE’s and 28% of wet soil STEs.

6. IMAGE PROCESSING CONDUCTED ON DIGITAL PHOTOGRAPHS TAKEN OF SOIL TRANSFER PATTERNS

Summary of image processing analyses conducted on digital photos recording the soil transfer patterns on fabric after STEs were conducted in the laboratory

Image processing software analysed digital photos taken of every soil transfer experiment (STE). Quantifiable numerical data was collected regarding the quantity of soil transferred, percentage of individual soil objects and aggregates, Munsell soil colour range and directionality of soil transferred. This data was then combined by soil sample, method of transfer and whether soil was moist or dry when the test was run; producing the following graphs and Rose diagrams.

Photographs were categorized by soil sample and further classified by wet or dry moisture content experiments. Image processing enabled quantifiable numerical data to be collected on the following key areas:

1. The quantity of different categories of soil particles (pale smears, brown smears and organic particles) were collated as a percentage of the total soiled fabric area in pixels and then compared with areas of clean fabric. The objects include solid clumps of soil, bark and plant fragments. There are also areas of stained fabric ("pale smears") probably due to the presence of dispersed clay and oxide in grains that are individually too small to recognise in these images. Visual inspection suggests the objects reported are very rarely single mineral grains. Some of the plant material is distinctly green and this is reported separately as "organic particles". However most of the plant material and especially bark was not distinguished from aggregates composed of soil minerals ("brown smears").
2. The approximate composition of individual soil objects and aggregates of soil objects (both greater than 2 pixels) making up this soiled fabric area were compared for each soil sample, which was further divided by wet or dry soil moisture content.
3. Directionality of soil clumps and stains, sorted by length/width >2 pixels, revealed the dominant direction in degrees that soil was transferred to the fabric when dragged from right to left across a soil surface. This numerical data was illustrated using rose diagrams created in GeoOrient. Three Soil Transference Experiments (STE) recorded in each category were combined into one rose diagram.
4. Standard Munsell colour hues, values and chromas were matched to the image processing software's 'Red Blue Green' (RGB) colour values. A 'colour standard' was created by analysing the average ratio of RGB values of the white colour of the scale bar incorporated into all original photographs. The colour ratios of 25 Munsell colour chips, originally allocated to one or more soil samples in optimum daylight conditions, were then analysed using digital photos of Munsell colours taken under the same lighting conditions in the laboratory. (Only seven soil samples were eventually chosen for these experiments). Any discrepancies in RGB values in individual photographs could then be adjusted for approximate brightness and colour differences using the 'colour standard' white scale bar. A range of dominant Munsell colours for each

soil sample, further separated by wet or dry moisture content, were recorded as a number of pixels (Appendix 3).

5. The smallest object in digital photographs that is consistently recognised by image processing classification is 2 pixels in area. From the scale bar in the images the typical pixel size was 40-60 microns; so the dimensions of the smallest objects recognised are 100 by 50 microns.

6.1 Quantity of soiled areas on fabric compared to clean areas of fabric

Soil objects recognised by image processing software as areas in pixels were categorised as pale smears, brown smears, organics as well as areas of clean fabric. Due to the software's difficulty in recognising organic objects, the true area of this category is not realistically represented in the following graphs Figure 6-1 to Figure 6-3. The image processing software could not reliably recognise soil objects <100 microns. Anthroposol soil samples from the Rose Garden gravel path (110.5.1-6.1) produced inconclusive results from near-identical soil samples (Figure 6-1). The brick fragment sample (110.6.2) produced 15-22% of pale smears with the remainder of the fabric staying clean.

Moist soil from the Rose Garden bed (110.7.1) produced a greater percentage of soiled fabric areas than the dry fabric STEs (Figure 6-2). The quartz gravel-rich anthroposol soil of the Japanese Garden (110.8.1) and undecomposed leaf litter covering natural soil under deciduous trees near RTBG's southeast boundary (110.9.1), showed a negligible difference in quantity of soil transferred to fabric in either wet or dry runs.

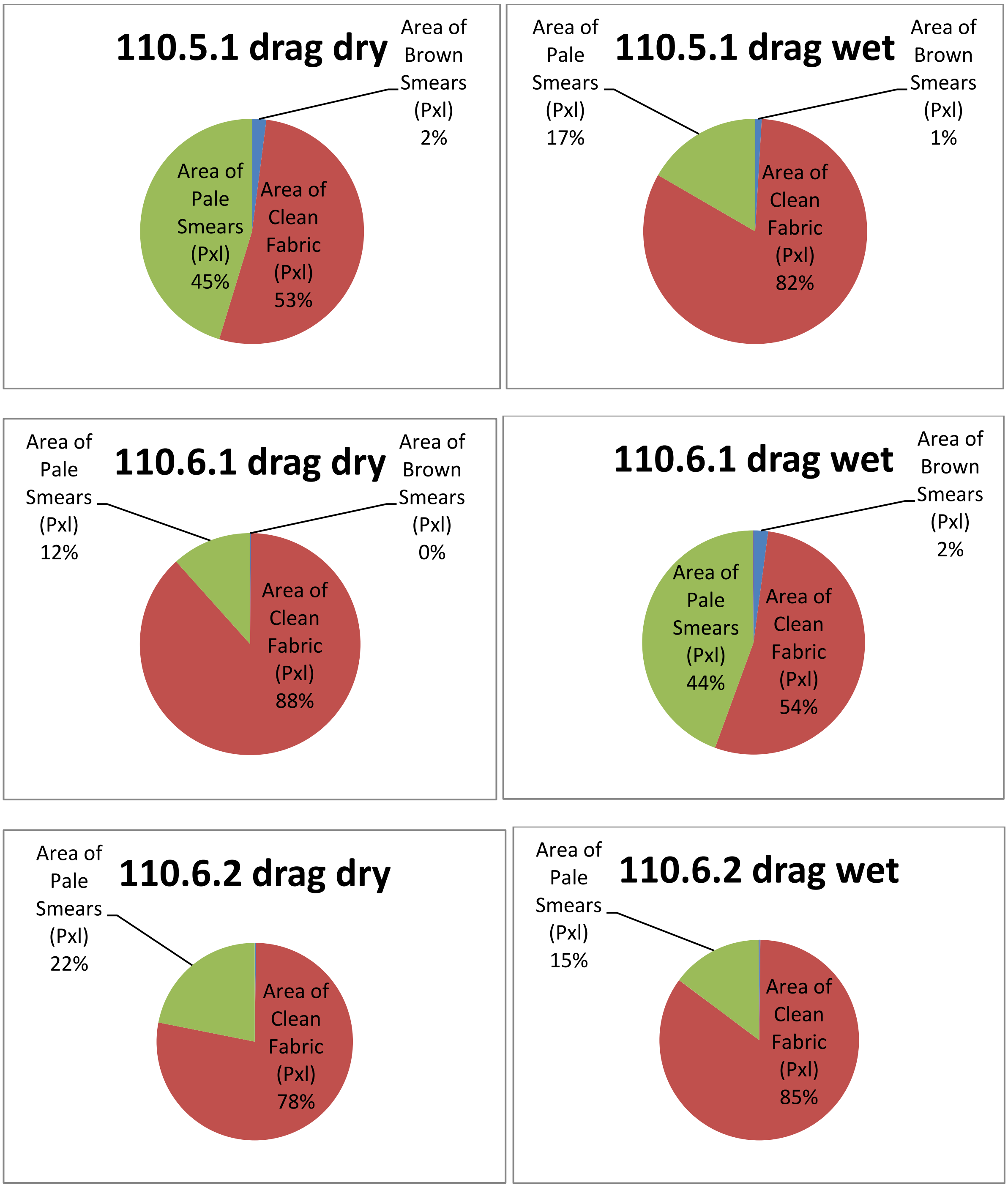


Figure 6-1 Quantity of dry and moist soil transferred to fabric from the Rose Garden path (110.5.1-6.1) and brick fragments found in lawn near the heritage brick wall (110.6.2), RTBG. Image processing showed these results as areas in pixels.

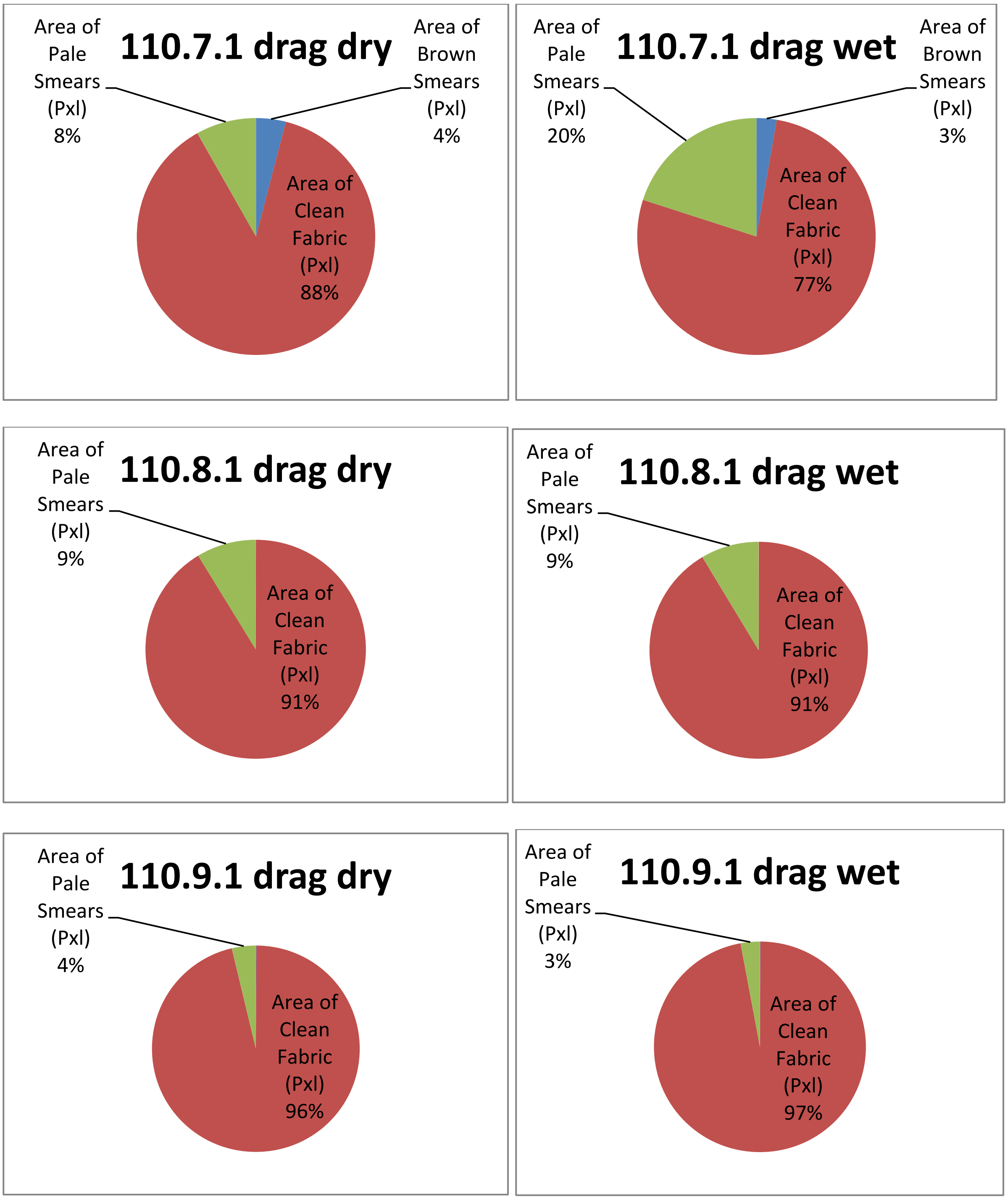


Figure 6-2 Quantity of dry and moist soil transferred to fabric from the Rose Garden bed (110.7.1), Japanese garden gravel (110.8.1) and undecomposed leaf litter covering natural soil (110.9.1), RTBG. Image processing showed these results as areas in pixels.

Natural soil (110.9.2) under deciduous tree leaves from the southeast boundary of the RTBG showed the greatest difference in the quantity of soil transferred when moist or dry soil was used, than the other anthroposol soil samples tested (Figure 6-3). Using this soil sample, only 1% of fabric area was recognised by image processing computer software as soiled when soil was dry. Whereas, 44% of the fabric area was recognised as covered by soil objects when soil was moist.

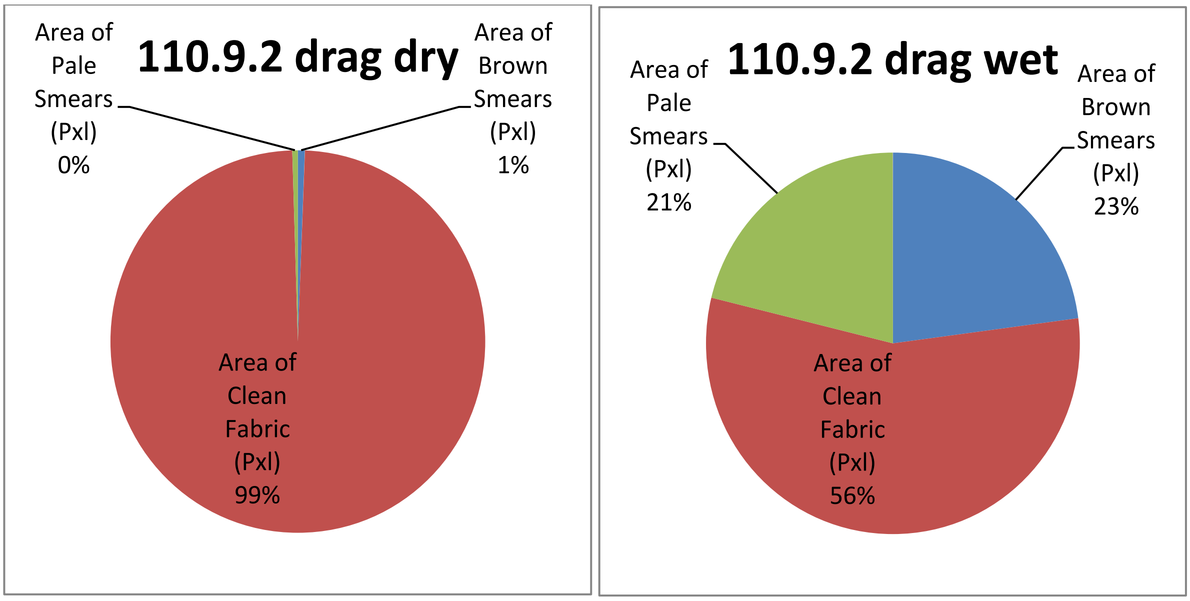
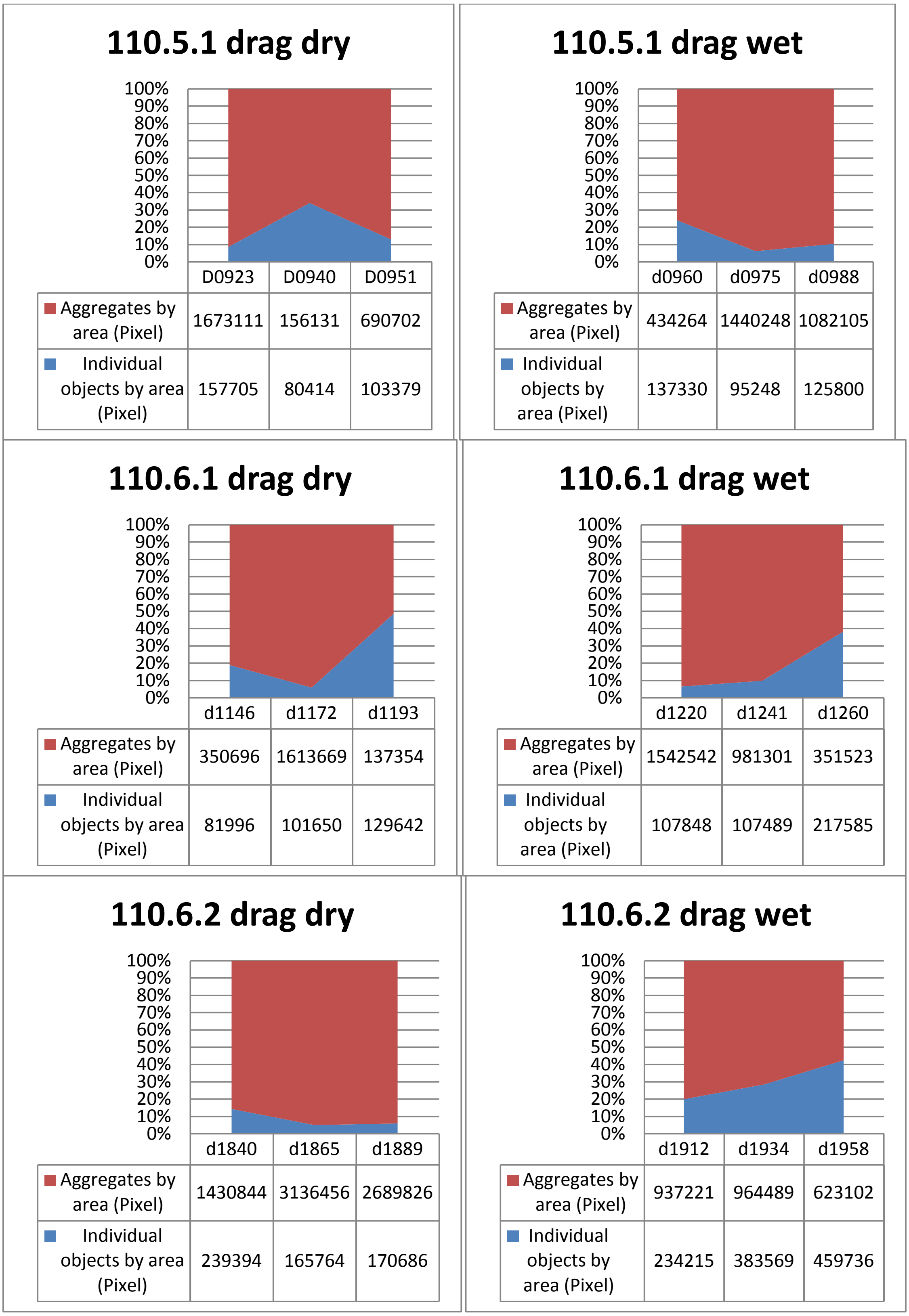


Figure 6-3 Quantity of dry and moist soil transferred to fabric from natural soil under deciduous tree leaves (110.9.2), RTBG. Image processing showed these results as areas in pixels.

6.2 Individual soil objects and aggregates of soil objects transferred to fabric

Soil samples from the Rose Garden path (110.5.1-6.1) showed the transfer of 10-50% of individual soil objects and 50-90% of aggregates of soil objects onto fabric when dry soil is used in the STE (Figure 6-4). When wet soil is used, 10-40% of individual soil objects and 60-90% of aggregates are transferred onto fabric.

Soil composed solely of brick fragments (110.6.2) showed 5-10% of individual objects and 90-95% of aggregates when transferred during a dry run onto fabric. When soil is wet, 20-40% of individual objects and 60-80% of aggregates were transferred onto fabric.



110.5.1 drag dry

	D0923	D0940	D0951
Aggregates by area (Pixel)	1673111	156131	690702
Individual objects by area (Pixel)	157705	80414	103379

110.5.1 drag wet

	d0960	d0975	d0988
Aggregates by area (Pixel)	434264	1440248	1082105
Individual objects by area (Pixel)	137330	95248	125800

110.6.1 drag dry

	d1146	d1172	d1193
Aggregates by area (Pixel)	350696	1613669	137354
Individual objects by area (Pixel)	81996	101650	129642

110.6.1 drag wet

	d1220	d1241	d1260
Aggregates by area (Pixel)	1542542	981301	351523
Individual objects by area (Pixel)	107848	107489	217585

110.6.2 drag dry

	d1840	d1865	d1889
Aggregates by area (Pixel)	1430844	3136456	2689826
Individual objects by area (Pixel)	239394	165764	170686

110.6.2 drag wet

	d1912	d1934	d1958
Aggregates by area (Pixel)	937221	964489	623102
Individual objects by area (Pixel)	234215	383569	459736

Figure 6-4 Individual soil objects and aggregates of soil objects transferred to fabric, shown as an area of pixels, from soil from the Rose Garden path (110.5.1-6.1) and brick fragments (110.6.2).

Soiled fabric from the Rose Garden bed (110.7.1) showed 30-70% of individual soil objects and 30-70% of aggregates transferred when dry soil was used (Figure 6-5). When soil was moist, 0-15% of individual objects and 85-100% of aggregates were transferred onto fabric.

Soil transferred to fabric from the Japanese Garden (110.8.1) showed 35-55% individual objects and 45-65% aggregates when soil was dry; and 10-40% of individual objects and 60-90% of aggregates when soil was moist.

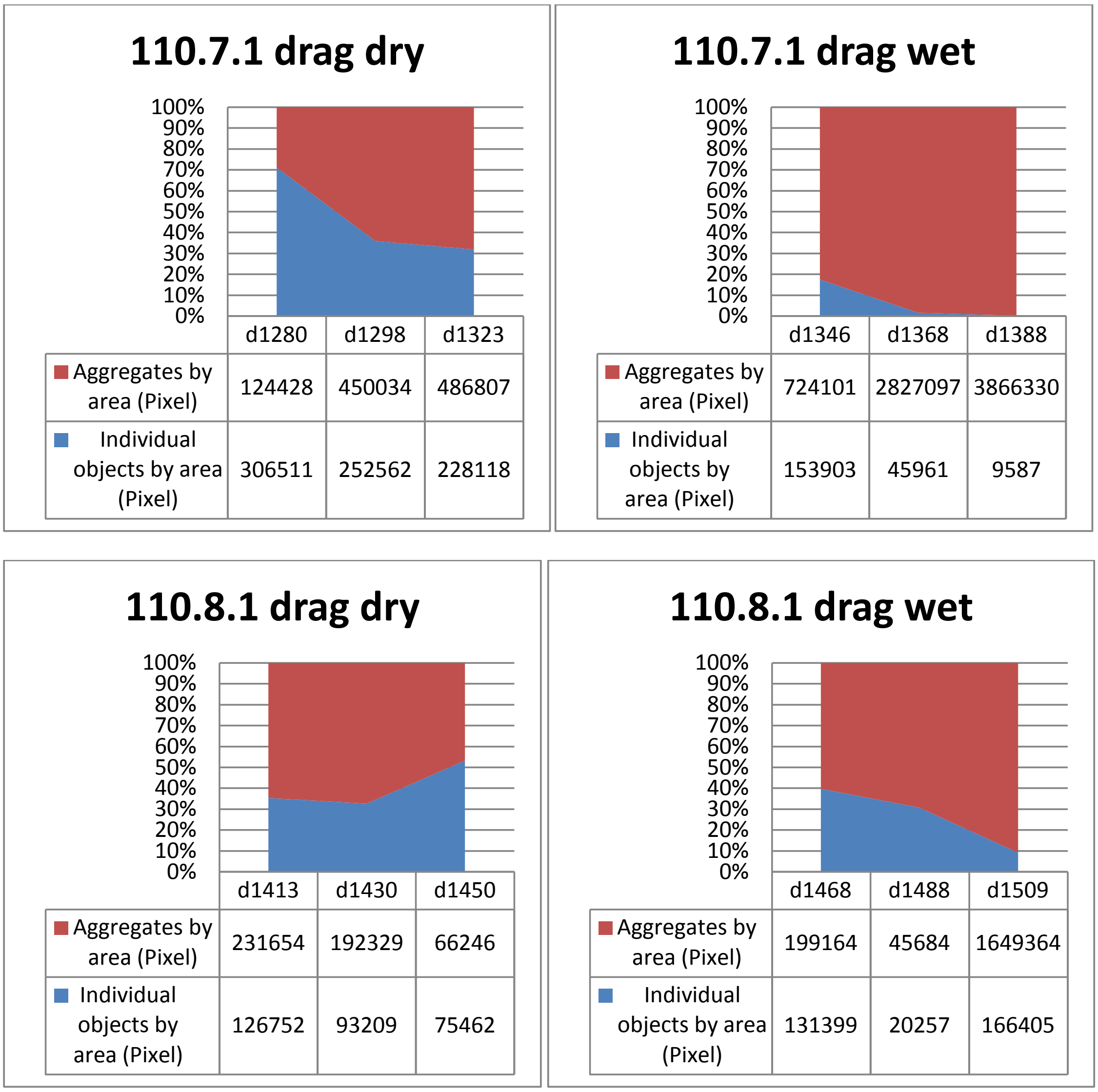


Figure 6-5 Individual soil objects and aggregates of soil objects transferred to fabric, shown as an area of pixels, from anthroposol soil from the Rose Garden bed (110.7.1) and quartz-rich gravel from the Japanese Garden (110.8.1).

The natural soil sample of leaf litter (110.9.1) transferred 30-50% of individual soil objects and 50-70% of aggregates when soil was dry; and 10-15% of individual objects and 85-90% of aggregates when soil was moist (Figure 6-6).
Natural soil lying directly beneath the leaf litter (110.9.2) transferred 25-55% individual soil objects and 45-75% of soil aggregates when dry and 10-15% of individual objects and 85-90% of aggregates when soil is moist.

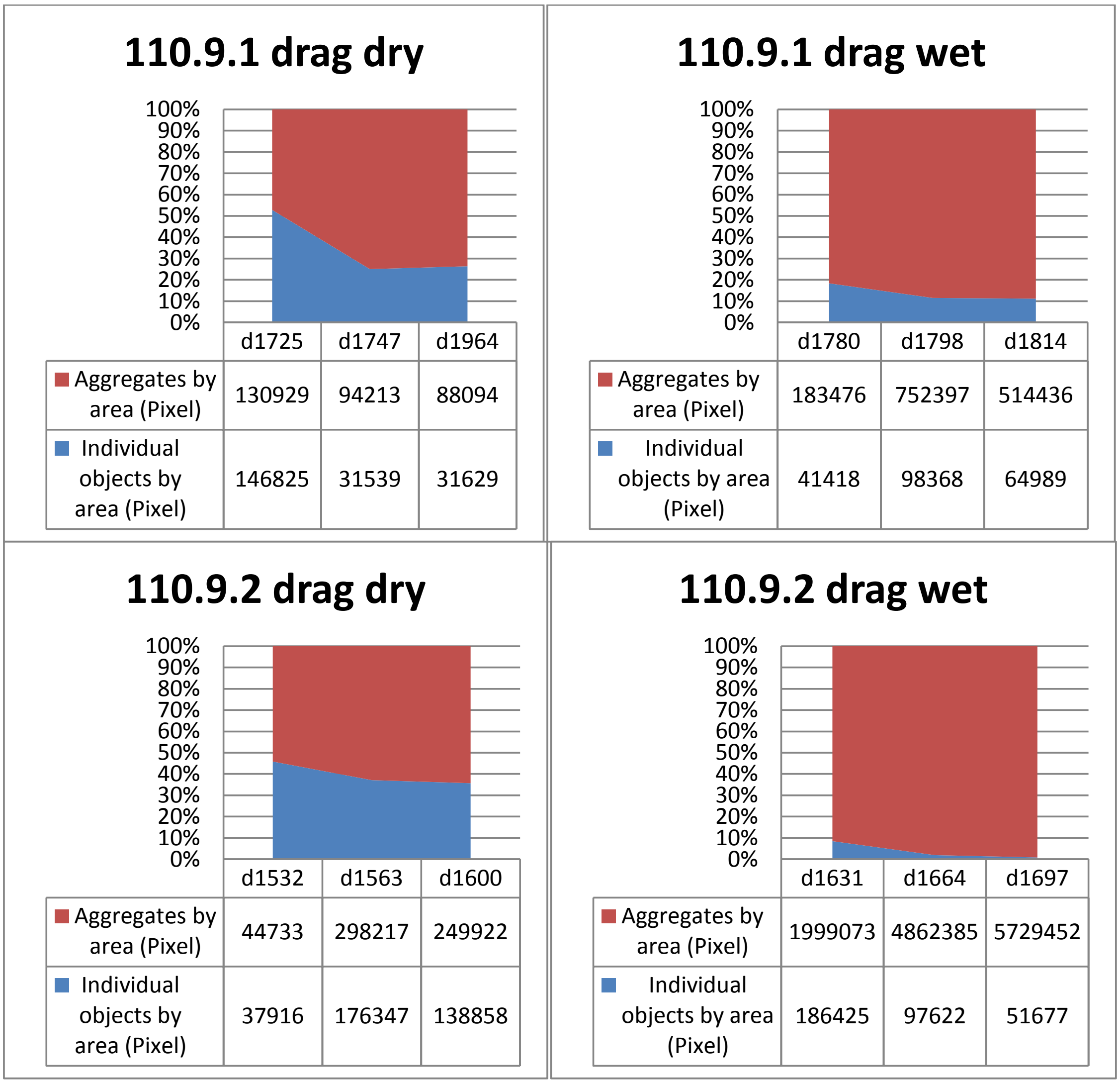


Figure 6-6 Individual soil objects and aggregates of soil objects transferred to fabric, shown as an area of pixels; from natural soil under trees from the southeast boundary of RTBG, composed of leaf litter (110.9.1) and surface soil (110.9.2).

6.3 Quantity of soil transferred to fabric analysed by soil type

Quantity of soil transferred to fabric was measured by image processing analysis using digital photographs taken of each STE. Computer analysis of the number of digital pixels, containing either individual or aggregate soil objects, provided a level of accuracy impossible by naked eye examination (Figure 6-4 to Figure 6-6). Soils were grouped by location and soil moisture content. Numerical data for individual and aggregate soil objects transferred from each soil sample to fabric, were combined and averaged.

Soil objects covering > 0.5 million pixels were classified as being a low quantity of soil transferred to fabric. Soil objects covering 0.5 million to >1 million pixels were classified as a moderate quantity of soil transferred. Soil objects covering 1 million pixels and higher were classified as a high quantity of soil transferred.

Anthropogenic gravel-rich sandy-loam soil from the Rose Garden paths (110.5.1-6.1) produced a low quantity of soil transferred when dry, increasing to moderate quantity of soil when wet. Brick fragments (110.6.2) produced high quantity of soil transferred when dry, decreasing to moderate quantity when wet. Anthropogenic organic-rich sandy loam soil from the Rose Garden bed (110.7.1) transferred a low quantity of soil to fabric when dry, increasing to high quantity of soil when wet. Anthropogenic quartz-rich gravel from the Japanese Garden (110.8.1) and natural leaves from the SE boundary (110.9.1) both produced trace to low quantity of soil to fabric when dry, increasing to low quantity when wet. Natural organic-rich loam from the SE boundary (110.9.2) produced low quantity when dry, increasing to very high quantity of soil transferred when wet.

6.4 Munsell soil colour range of soil transferred to fabric in pixels

The fine (<2mm) wet and moist fractions of each soil sample had their Munsell soil colour analysed by naked eye outside under natural daylight (see Table 2-2). Twenty-five different Munsell colours were recognised. When image processing software analysed digital photographs taken under artificial lighting conditions inside MRT laboratories for their Munsell colour, this limited range of Munsell colours were used to match the computer softwares RGB values to the standard Munsell soil colours used by forensic and agricultural soil scientists. Because artificial light drastically affects the colour of the Munsell colour chips, these 25 colours were photographed again in MRT laboratories under the same artificial lighting conditions; with an aim to ensure the most accurate recognition by image processing software of the Munsell colours of trace soil transferred.

For each soil sample, using either dry of moist soil, a set of three STEs was combined to produce a single graph (Figure 6-7 to Figure 6-13). The fine (<2mm) fraction of soils from the Rose Garden path (110.5.1), under natural daylight, showed a Munsell colour of 7.5YR 5/2 when dry and a darker 7.5YR 3/2 when moist (Table 2). However, soil transferred onto fabric and photographed under artificial lighting conditions, was analysed by image processing software as displaying a dominant colour of 2.5YR 6/1 when soil transferred was dry; with minor peaks at 7.5YR 2.5/2, 5.2 and 10YR 6/3 and 7/2. When moist, trace soil displayed three dominant Munsell colour peaks at 2.5YR 6/1, 10YR 6/3 and 7/2. Minor peaks were identified at 7.5YR 2.5/2 and 5/2 (Figure 6-7).

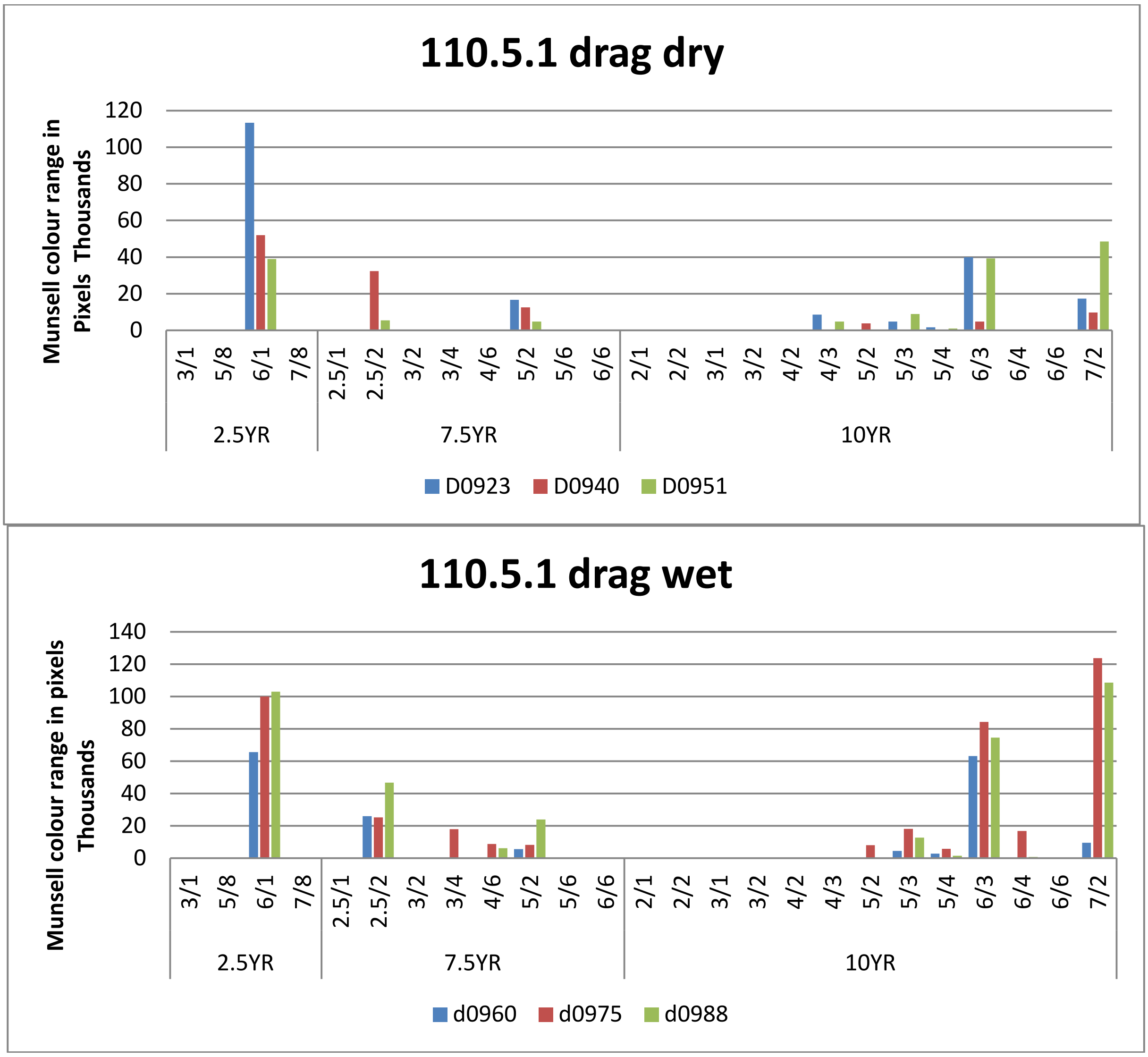


Figure 6-7 Munsell soil colour range recognised by image processing software of soil from the Rose garden path (110.5.1) transferred onto fabric when soil was dry and moist.

The other soil sample taken from the Rose Garden path (110.6.1), under natural daylight, showed the same fine fraction Munsell colours as 110.5.1; being 7.5YR 5/2 when dry and a darker 7.5YR 3/2 when moist (Table 2-2).

Image processing software recorded the colour of soil transferred to fabric as sharing dominant peaks at 2.5YR 6/1 and 7.5YR 2.5/2 when dry; with minor peaks at 7.5YR 3/4, 5/2 and 10YR 6/3. When moist, three dominant peaks were identified as 2.5YR 6/1, 10YR 6/3 and 7/2 (Figure 6-8). Minor peaks were revealed in a cluster at 7.5YR 2.5/2, 3/4, 4/6 and 5/2 plus 10YR 5/3.

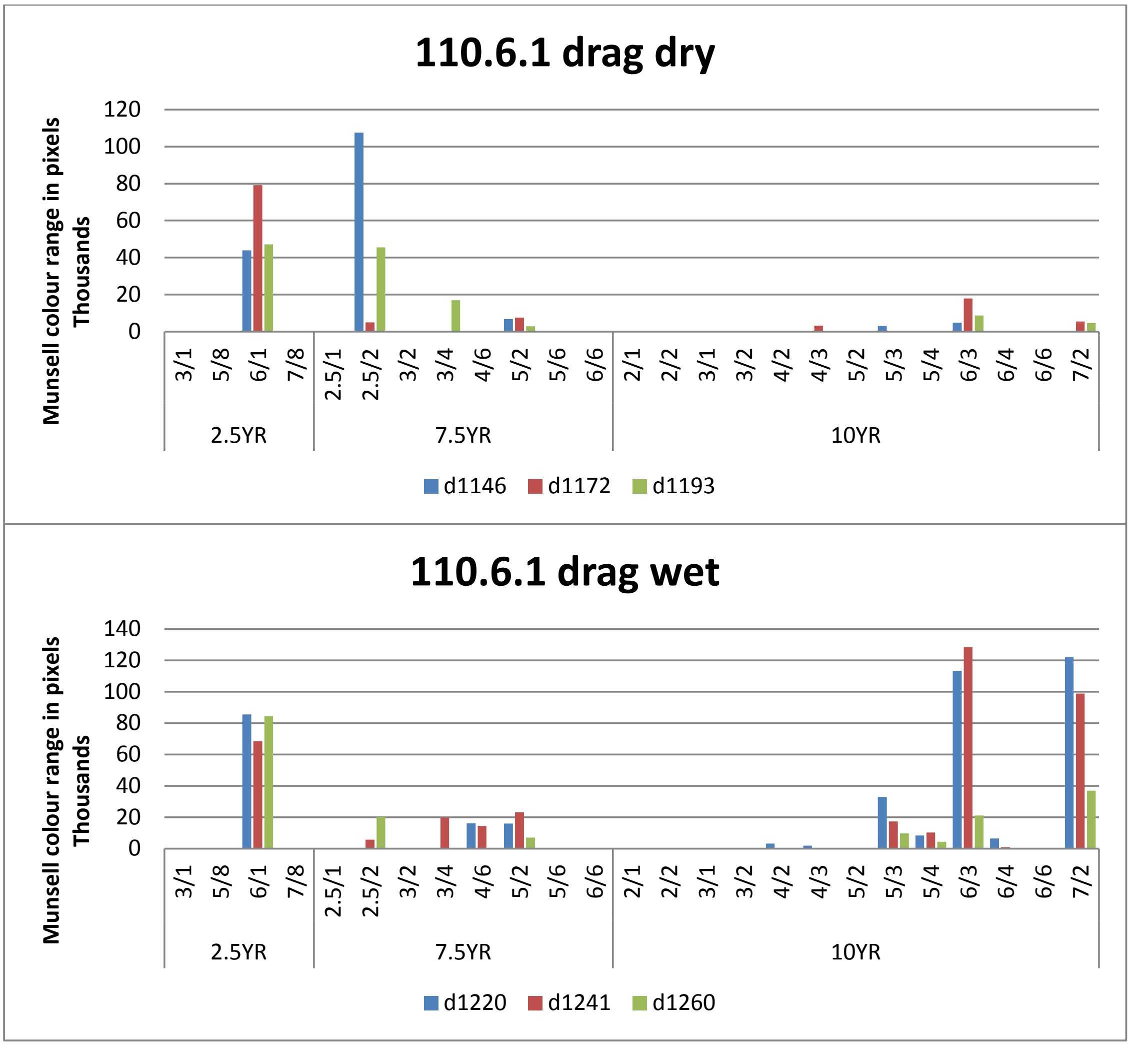


Figure 6-8 Munsell soil colour range recognised by image processing software of soil from the Rose garden path (110.6.1) transferred onto fabric when soil was dry and moist.

The soil sample composed of brick fragments taken from lawn near the heritage brick wall (110.6.2), under natural daylight, showed a fine fraction Munsell colour of 2.5YR 7/8 when dry and a darker 2.5YR 5/8 when moist (Table 2-2).

Image processing software recorded the colour of soil transferred to fabric as having a dominant peak at 2.5YR 6/1 when dry and a main peak when moist of 2.5YR 6/1, with a lesser peak at 7.5YR 2.5/2 (Figure 6-9).

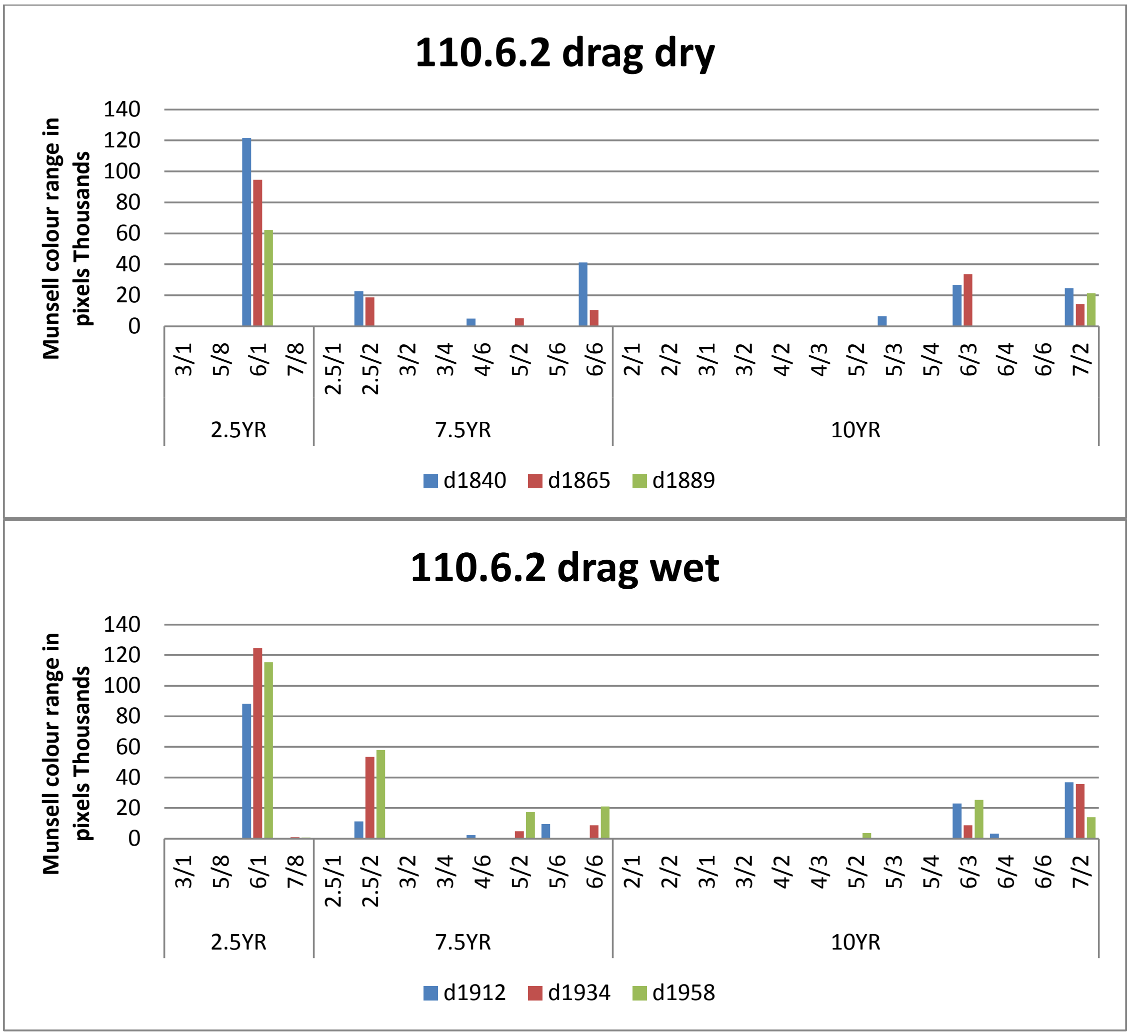


Figure 6-9 Munsell soil colour range recognised by image processing software of soil composed of brick fragments from lawn areas near the heritage brick wall (110.6.2) transferred onto fabric when soil was dry and moist.

The soil sample from the Rose Garden bed (110.7.1), under natural daylight, showed a fine fraction Munsell colour of 7.5YR 2.5/1 when dry and a darker 10YR 2/1 when moist (Table 2-2).

Image processing software recorded the colour of soil transferred to fabric as having a dominant peak at 7.5YR 2.5/2 when dry; with minor peaks at 7.5YR 3/2, 3/4, 5/2 and 10YR 6/3. When moist, a main peak was identified at 7.5YR 3/4; with a cluster of minor peaks at 7.5YR 2.5/2, 3/2, 10YR 6/3 and 7/2 (Figure 6-10).

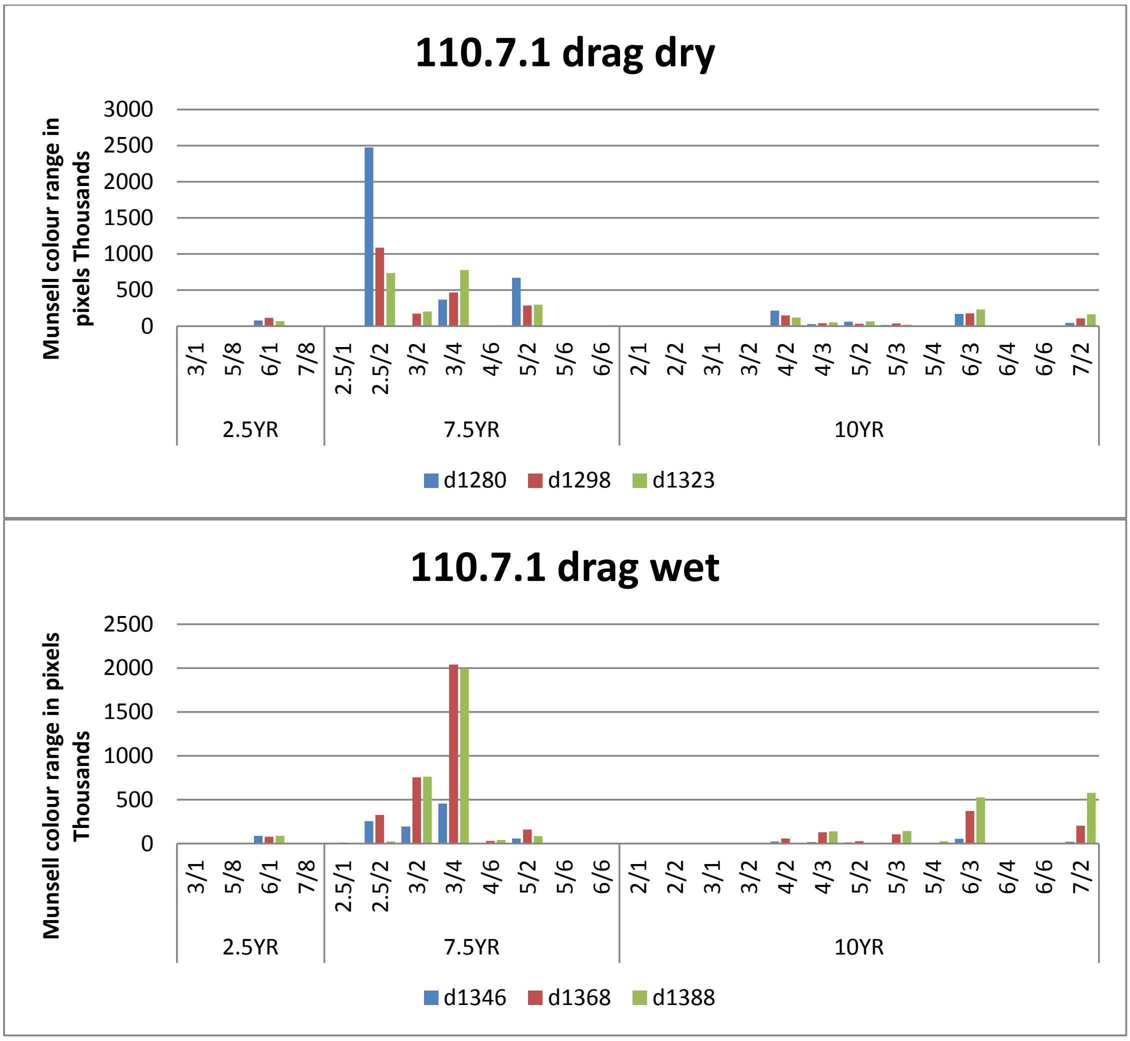


Figure 6-10 Munsell soil colour range recognised by image processing software of soil from the Rose Garden bed (110.7.1) transferred onto fabric when soil was dry and moist.

The quartz gravel-rich soil sample from the Japanese Garden (110.8.1), under natural daylight, showed a fine fraction Munsell colour of 2.5YR 6/1 when dry and a darker 2.5YR 3/1 when moist (Table 2-2).

Image processing software recorded the colour of soil transferred to fabric as having three dominant peaks when dry at 2.5YR 6/1, 7.5YR 2.5/2 and 3/4 when dry; with minor peaks at 10YR 6/3 and 7/2. When moist, two dominant peaks at 2.5YR 6/1 and 7.5YR 2.5/2 were identified; with minor peaks at 7.5YR 5/2, 10YR 6/3 and 7/2 (Figure 6-11).

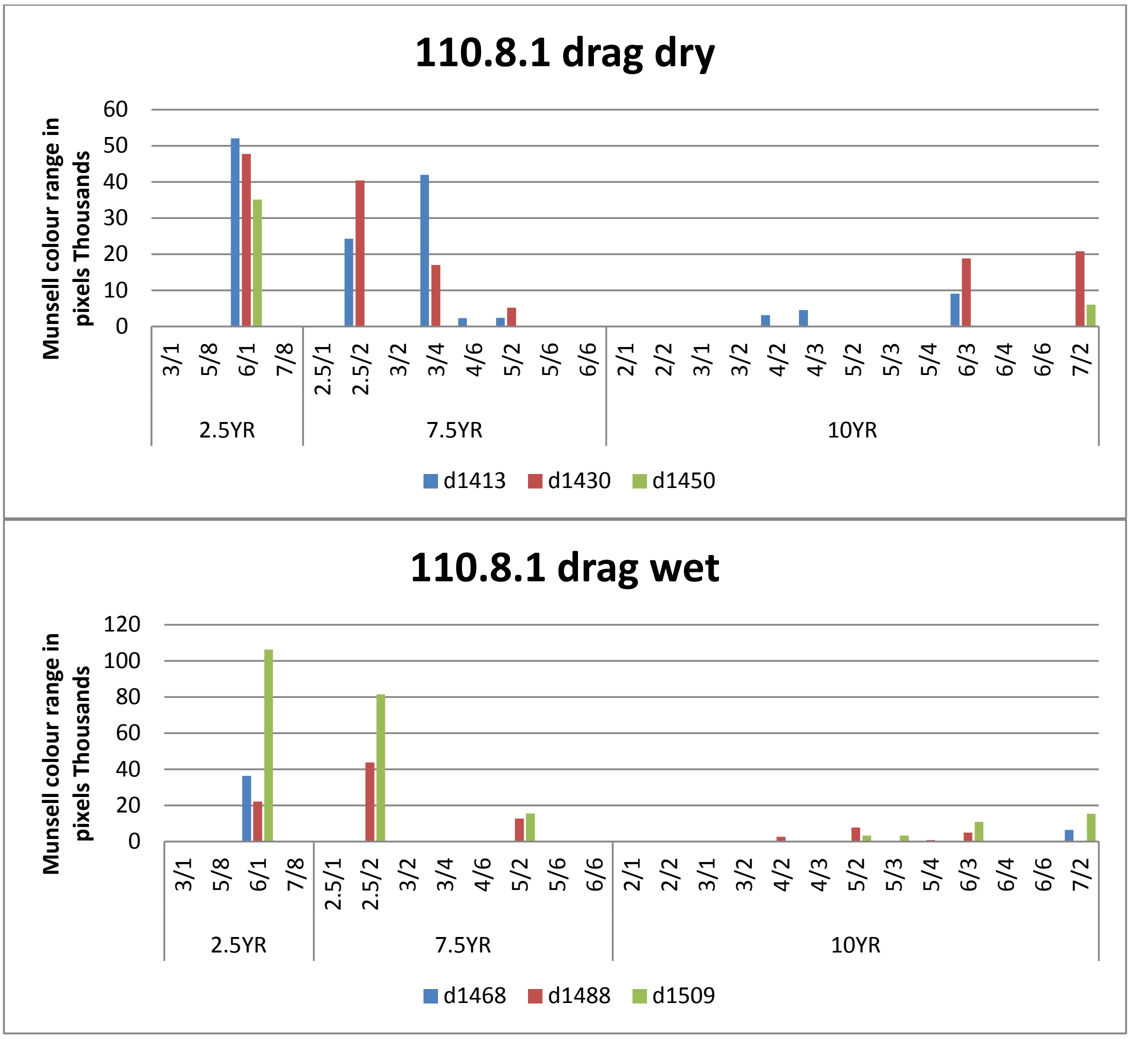


Figure 6-11 Munsell soil colour range recognised by image processing software of soil from the Japanese Garden (110.8.1) transferred onto fabric when soil was dry and moist.

The natural soil sample composed of undecomposed leaves (110.9.1) was not analysed by naked eye for a Munsell soil colour.

Image processing software recorded the colour of particles of undecomposed leaf matter transferred to fabric as having a dominant peak when dry at 7.5YR 2.5/2 when dry; with minor peaks at 2.5YR 6/1, 7.5YR 3/4 , 5/2 and 10YR 6/3 and 7/2. When moist, a cluster of dominant peaks at 7.5YR 2.5/2, 10YR 6/3 and 7/2 are identified; with minor peaks at 2.5YR 6/1, 7.5YR 3/4 and 5/2 (Figure 6-12).

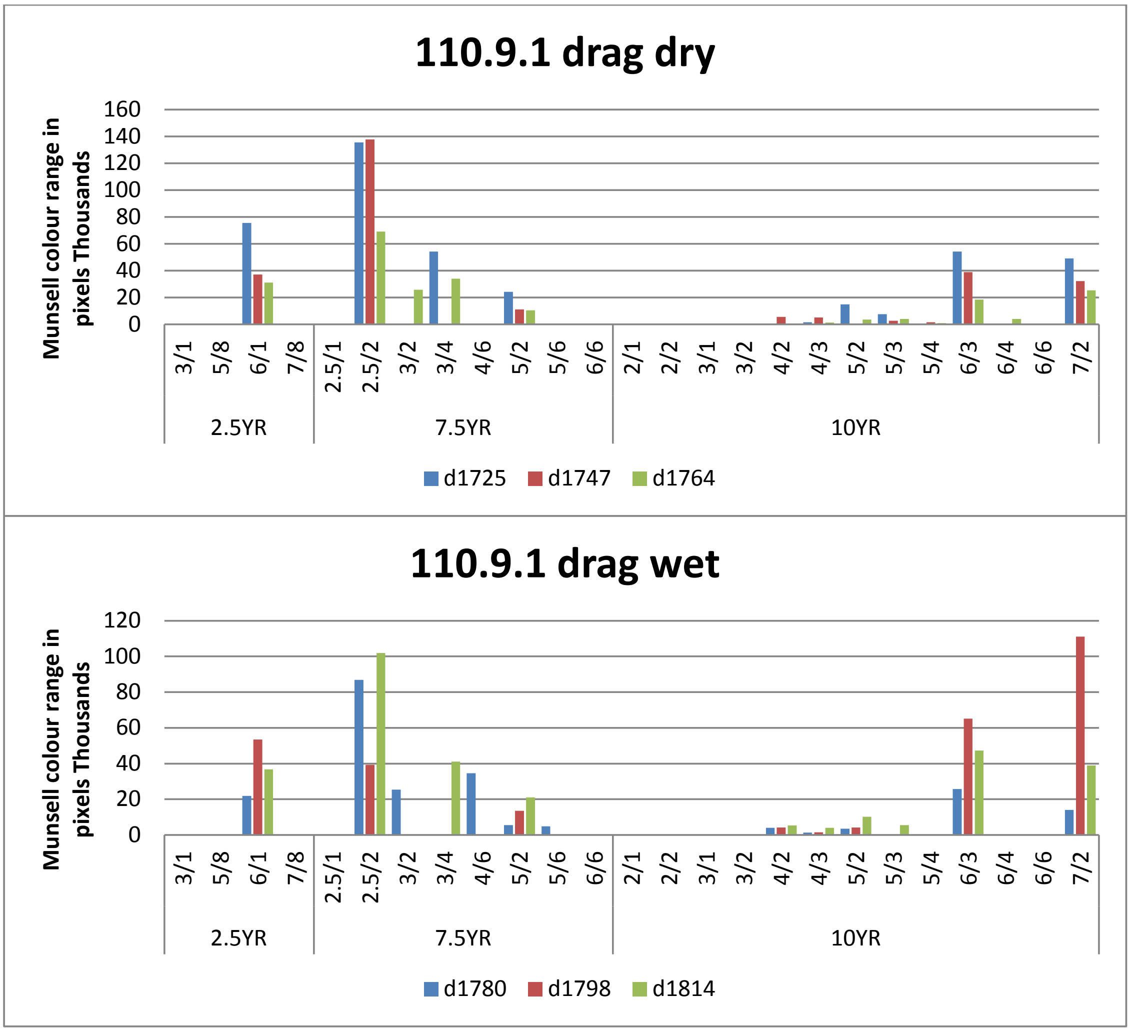


Figure 6-12 Munsell soil colour range recognised by image processing software of soil of undecomposed leaf litter covering natural soil on the southeast boundary of RTBG (110.9.1) transferred onto fabric when soil was dry and moist.

The natural soil sample underlying the leaf matter (110.9.2), under natural daylight, showed a fine fraction Munsell colour of 7.5YR 2.5/2 when dry and a darker 10YR 2/2 when moist (Table 2-2).

Image processing software recorded the colour of soil transferred to fabric as having dominant peaks when dry at 7.5YR 2.5/2 and 3/4; with minor peaks at 7.5YR 3/2 and 2.5YR 6/1 and 10YR 6/3. When moist, a cluster of dominant peaks are identified at 7.5YR 2.5/2, 3/2 and 3/4; with minor peaks at 2.5YR 6/1, 7.5YR 5/2, and 10YR 6/3 (Figure 6-13).

In order to further identify the level of analysis that image processing can provide forensic soil investigators, a single graph was also produced for every soil transfer pattern photographed (Appendix 3). A very similar range of Munsell soil colours was appearing in each of the three soil transfer patterns analysed by image processing. The tremendous potential of image processing analysis to accurately identify and compare the Munsell colour of trace soil evidence on fabric, without requiring a spectrophotometer, is detailed in the 'Discussion' section of this paper.

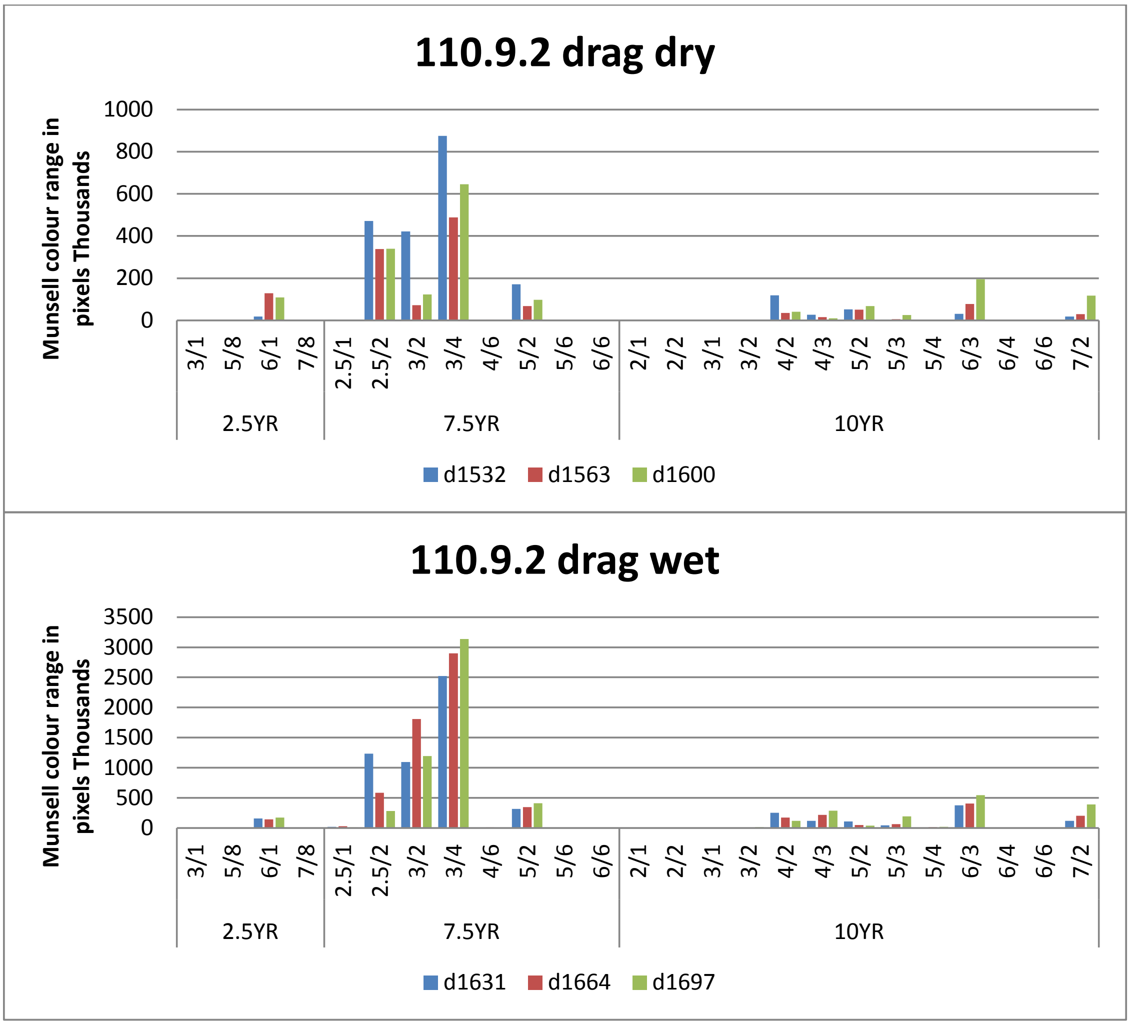


Figure 6-13 Munsell soil colour range recognised by image processing software of natural soil on the southeast boundary of RTBG (110.9.2) transferred onto fabric when soil was dry and moist.

6.5 Directionality

Often it is desirable to present orientation data in such a way that the distribution of orientations is emphasised independently of the geographic location of data; such as whether there is a pattern of preferred orientation of the soil patterns in an area on the bras. The types of diagrams most frequently used to present such information are histograms, rose diagrams and spherical projections (Allaby and Allaby 1999). Rose diagrams are essentially histograms for which the orientation axis is transformed into a circle to give a true circular plot. They are commonly used in structural geology to plot the orientation of joints and dykes. Wind directions and frequencies are also be plotted on rose diagrams.

Using directional numerical data provided by image processing software, Rose diagrams illustrated the directionality of moist and dry soil particles transferred onto fabric (Figure 6-14). This methodology was important to objectively prove that any directional patterns recognised by the human eye, could also be identified by computer software. This objectivity is important during criminal investigations using forensic soil evidence.

Rose diagrams mapped the directionality of thousands of soil particles over 2 pixels diameter. This method consistently created a simple yet definitive pictorial record of the soil transferred onto fabric during dragging experiments. Each Rose diagram only took minutes to create, relying upon image processing directional numerical data.

Strong uni-modal directionality was displayed when fabric was dragged in one direction across the soil surface. This was demonstrated by the black directional lines reaching the edges of the rose diagram, with a distinct horizontal line trending right to left. Dry soil particles had a greater tendency than moist soil to gather against the bra's perpendicular middle seam; producing more of a bi-modal directionality. Dry soil had a greater percentage of individual soil objects. This would create a more scattered and random directionality than the same soil wet. During soil transfer experiments using a soil sample from the Japanese garden (110.8.1) composed of 90% white gravel and a natural soil sample composed entirely of undecomposed leaves (110.9.1), with negligible mineral soil content, minimal trace soil was transferred to the bra fabric. Despite this minute amount of trace soil quantified by image processing software, the Rose Diagrams created still recorded a strong uni-modal directionality; very similar to soil transfer results using other soil samples with higher amounts of fine clay-sized soil particles.

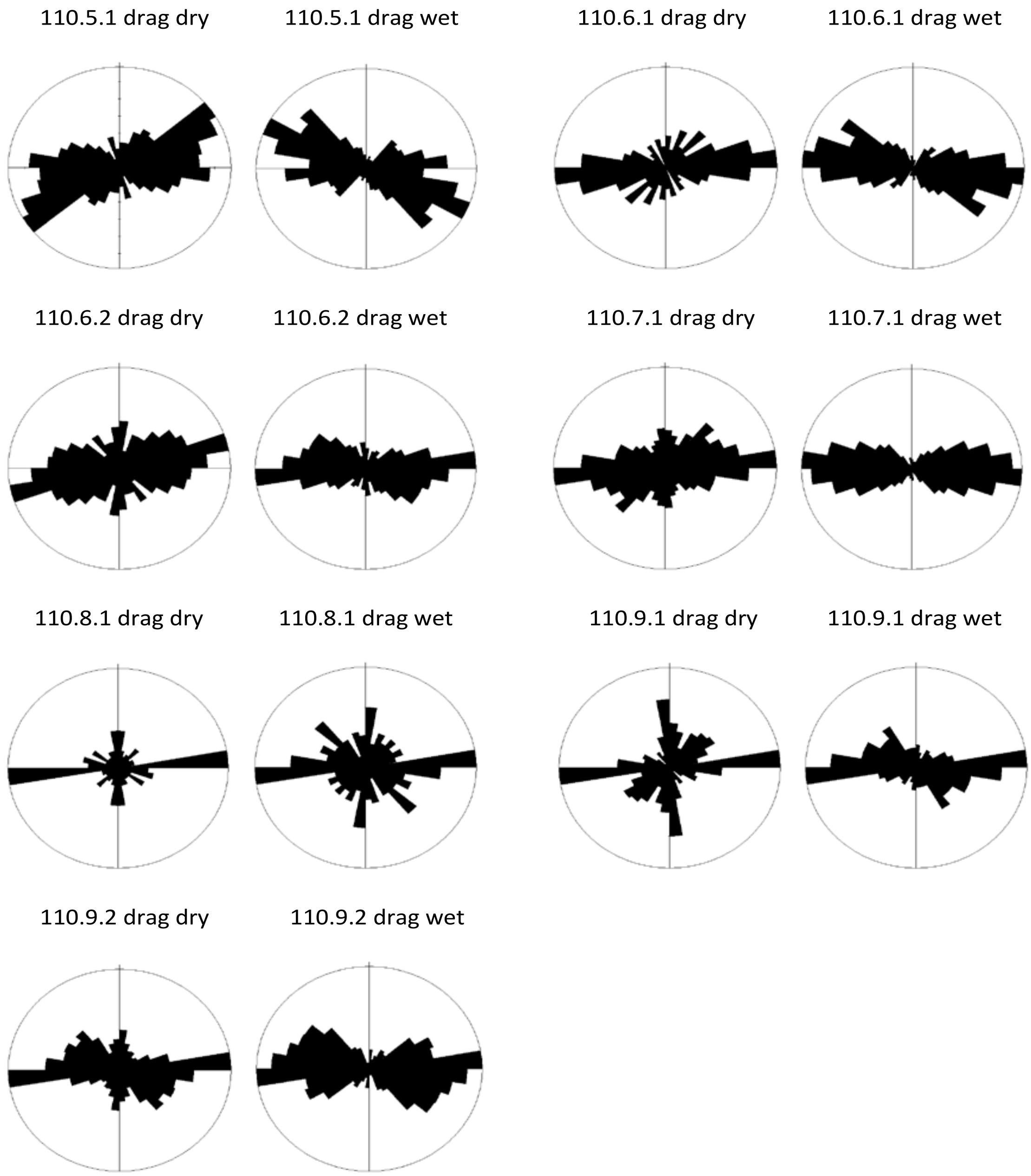


Figure 6-14 Rose diagrams of the directionality of dry and moist soil transferred onto fabric during STEs. Strong uni-modal directionality was produced when fabric was dragged from right to left across the soil surface. Dry soil particles had a greater tendency than wet soil to gather against the middle seam, creating more of a bi-modal directionality.

7. DISCUSSION

This report has focused on the soil transfer method of dragging weighted clothing (bra) across a wide range of soil surfaces, to simulate a female victim being dragged during the perpetration of a crime. Therefore, this set of soil transfer patterns cannot indicate other modes of transfer, such as placing loose or weighted clothing on a soil surface or a combination of several methods. It is our intention to write subsequent reports and papers describing different modes of transfer, to be used by Police and forensic investigators at crime scenes.

7.1 Size and quantity of soil particles transferred in STE

The majority of soil particles transferred in all STEs were very fine silt or clay-sized fragments. The largest fragment transferred was a 5mm x 4mm brick fragment from sample 110.6.2 (Figure 3-4). When the 2kg weight was removed, the larger (>0.5cm) loose fragments were easily dislodged and moved across the bra's surface; often accumulating in the bottom of the storage bag. Whereas, the fine fractions, such as those transferred in sediment trails, tended to remain in situ; half-embedded in the fabric.

7.2 How soil texture and mineralogy affected the resulting Soil Transfer Patterns

The texture of the seven soil samples used in these experiments was either loamy-sand, sand, brick or undecomposed leaves (McDonald and Isbell 2009). All textures produced soil transfer patterns in every test, to a greater or lesser extent (Table 4-1). The soil samples with the texture of loamy-sand produced the most easily identifiable soil transfer patterns; possibly due to the organic carbon content of these soil samples. These dark, loamy-sand samples produced soil transfer patterns that were the easiest to identify on the white fabric of each bra (See Figure 5-2, Figure 5-3, Figure 5-7, Figure 5-10).

A soil sample's clay content greatly influenced the resulting soil transfer patterns; as well as the quantity and persistence of soil particles transferred. Fine clay-sized particles showed greatest adherence or persistence on the fabric when both wet and dry soil was used. Clay particles also acted as a 'mortar' to secure larger grains or aggregates of soil (See Figure 5-2 and Figure 5-7).

7.3 How moisture content of soil affected the resulting Soil Transfer Patterns and the persistence of trace soil on the fabric

As revealed in the results of these STEs, whether soil is wet or dry when transferred onto clothing can have a major influence on the ease of visual identification of soil transfer patterns, the amount and particle size of soil transferred, it's adherence to the fabric and the mineralogy of particles transferred.

Fine clay-sized particles showed greatest adherence or persistence on the fabric when both wet and dry soil was used. Their persistence was greatly enhanced when soil was moist; enabling these soil particles to not only coat but impregnate the fabric fibres (See Figure 5-2 and Figure 5-7).

7.4 Discussion of XRD and NDIR analysis of soil samples from Royal Tasmanian Botanical Gardens

To compare the effect of soil mineralogy on resulting transfer patterns, all soil samples underwent analyses using powder X-ray diffraction. If soils tested were vastly different in mineralogical composition, this might imply a 'universality' to transfer patterns seen across all soils tested. Soil mineralogical results are summarised in Table 3-1.

High clay content soils included the two spolic Anthroposols from the Rose Garden path; consisting of 90% sandstone and mafic igneous gravel with negligible organic content. Mineralogy was approximately 40% weight of quartz, with 20% of both plagioclase and smectite clay. Humose mesotrophic brown dermosol (Sth-E-bound-Nat) also had similar levels of quartz and smectite clay content to Rose garden path soils, but differed with its high organic content of 38% weight.

Hortic anthroposol (Rose garden bed) was 69% weight quartz with organic content of 24%. Another spolic anthroposol (Japanese garden soil) had high quartz content (83%), minimal clay or organic content. Brick fragments (110.6.2) had high quartz content, with negligible organic content and traces of mullite, calcite, rutile and hematite. The greatest differences between soils were the carbon levels; ranging from 0.26-3.10% in the gravel-rich Anthroposols. In contrast, 14% carbon was measured in the Rose garden bed soil and 22.8% carbon in SE boundary underlying natural mineral soil (Table 3-2). Small Sulfur contents were noted but no Sulfur-bearing species identified; generally correlating with organic matter.

7.5 Discussion of Image Processing quantitative numerical data of soil transfer patterns on fabric

Image processing of digital photographs taken of soil transferred onto fabric was undertaken to provide an objective approach to graphically present soil transfer patterns. This more quantitative graphical presentation of soil patterns assisted or confirmed the interpretation of soil transfer patterns such as directionality of soil transferred; whilst adding a standardised objectivity to the results not possible through identification by naked eye alone.

Image processing of all soil objects ≥2 pixels diameter (>100 microns) were collated; including the quantity of soil transferred, percentage of individual soil objects and aggregates, Munsell soil colour range and directionality of soil transferred. Due to limitations in the software's programming, the smallest soil particle that could be reliably identified was >100 microns.

Difficulties differentiating mineral from organic soil objects could feasibly be overcome with more complex programming. Both Rose garden path soils and mineral-based SE boundary natural soil had smectite clay content between 15-20% weight. A much greater quantity of soil objects, in particular soil aggregates, were transferred to fabric when these soils were moist.

Classifying soils for a particular purpose involves the ordering of soils into groups with similar properties and for potential end uses. In general, soil classification systems currently used in most countries involve the use of the following three broad approaches (Fitzpatrick 2013a).

- General-purpose broad soil classifications such as World Reference Base (World_Reference_Base 2014), which communicate soil information at international scales; and national scale classifications, such as Australian Soil Classification (Isbell 2002), shown in Table 1.
- State, provincial or regional soil classifications, which are designed both to assist with ‘‘user-friendly’’ communication of soil information and to account for the occurrence of soils that impact on existing and future industry development and prosperity (Fitzpatrick 2013a).
- Special-purpose and more technical soil classification systems, which are used for local or single-purpose applications such as in Soil Forensics (Fitzpatrick 2013a). These Special-purpose systems generally involve using plain language names for soil types for users such as police [42] but must also correlate with the general-purpose international and national classifications as shown in Table 3.

Using image processing numerical data that measured the quantity of soil objects (both individual and aggregates) transferred to fabric, a relationship between soil type, clay (smectite) and soil moisture content was discovered.

Anthropogenic, gravelly, sandy loam soil (Table 2) with high organic carbon content (Rose garden paths), produced a low-moderate quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to moderate quantity when wet (dark brown).

Anthropogenic, brick fragment-rich soil with high quartz and negligible organic and smectite content (Brick-Anth), produced a high quantity of reddish-grey soil objects when transferred to the fabric when dry, decreasing to moderate quantity when wet (reddish grey).

Anthropogenic organic-rich sandy loam soil with approximately 15 to 19 % smectite and high amounts of arkosic sandstone and andesitic-to-weathered mafic igneous rock (Rose garden beds) produced a low to moderate quantity of reddish-grey soil objects when transferred to the fabric when dry and increasing to a high quantity when wet (light-grey to reddish grey).

Anthropogenic, quartz-rich, gravelly, sandy soil with high quartz content and negligible organic and smectite content (Japan-bed-Anth), produced a trace grey coloured soil transference pattern to fabric when dry, increasing to a low quantity when wet.

Natural organic-rich soil with very high organic carbon content (Non-mineral based horizon Sth-E-bound-Nat leaves), produced a trace quantity of very dark brown soil objects when transferred to the fabric when dry and increasing to low quantity when wet (very dark brown).

Natural loamy soil with approximately 20% smectite (Sth-E-bound-Nat underlying mineral soil) produced a moderate quantity of dark brown soil objects when transferred to the fabric when dry and increasing to high quantity when wet (dark brown).

Smectite is highly susceptible to soil moisture and soils with high smectite content can undergo as much as a 30% volume change; an indication of smectite’s shrink/swell potential (Weaver 1990). This characteristic of smectite clay may help explain the differences seen in trace soil patterns when dry or moist soil was transferred to fabric.

Both Japanese garden soil (110.8.1) and Brick fragments (110.6.2), with high quartz content and negligible organic and smectite content, transferred minimal trace soil to fabric; as did the natural soil horizon composed of undecomposed leaves. (which did not undergo XRD analysis.)

In the seven soil samples tested, the greatest quantity of soil transferred onto fabric was from mineral-based underlying natural soil sample 110.9.2 (Figure 6-6). The least soil transferred came from Anthroposol (human-made) gravel-rich soil from the Rose garden path (110.5.1-6.1) (Figure 6-4), Japanese Garden (110.8.1) (Figure 6-5) and natural soil composed of undecomposed leaves (110.9.2).

In all soil samples, aggregates of soil objects made up approximately two-thirds of all soil objects detected by image processing. Dry soil samples provided the greatest percentage of individual soil objects, with moist soil producing a greater area of aggregates.

Because photographs of trace soil patterns were taken using a very basic 14.1 megapixel digital camera under artificial lighting in the laboratory, it was correctly predicted that initial Munsell colours chosen for soils by naked eye in natural daylight would differ from those detected by image processing software.

Despite the limitations of these source photographs, image processing chose the same colour for dry Japanese garden soil. Dry SE boundary underlying natural mineral soil had a semi-dominant peak of the same Munsell colour chosen under natural daylight. Dry Rose garden bed soil was only one Munsell colour shade different than the initial Munsell colour chosen for dry fine soil fraction under natural daylight. When Munsell colour results are so close, the variability of the human retina must also be considered.

Only SE boundary underlying natural mineral soil produced clusters of neighbouring Munsell colours in dry and moist trace soil transferred. Other soils produced more distant Munsell colour peaks.

Not only did image processing software create a range of Munsell colours using photographs of trace soil on fabric, the same range of Munsell colours was correctly identified from trace soil on twelve different bras; linking this trace soil 'evidence' to the Rose Garden path. Using two soils sampled only four metres apart, image processing matched the same dominant peaks of Munsell colours in both dry and moist trace soil on fabric.

Comparing graphs of image processing numerical data of all soil samples revealed this software identified the same range of specific Munsell colours in individual photographs of STEs. The power of image processing to identify Munsell colour ranges to link trace soil on clothing to a specific location may prove as integral to forensic soil investigation as XRD's ability to identify peaks of soil minerals.

A thorough comparison between the three STEs done for each dry and wet soil sample discovered that image processing software could identify the same range of specific Munsell colours in all three photographs (Appendix 4). Looking at the peaks of colour shared between each set of three photographs was reminiscent of looking at DNA 'fingerprint' bands; where each 'band' in a child's DNA fingerprint must also be present in the fingerprint of one or other (or both) of the parents.

In forensic soil science, XRD analysis of soil provides a proven method of analysing the mineral composition of trace soil evidence on clothing. But in cases where soil evidence from multiple locations share very similar mineralogy, image processing the colour of trace soil evidence using digital photographs may provide a new objective, accurate and detailed method to compare and contrast soil evidence by colour alone.

This new level of detail in Munsell colour analysis was accomplished using no other source but digital photographs of the STEs taken in the lab under artificial lighting conditions. The resolution of this digital camera was only 14.1 megapixels.

Further research using image processing to analyse crime scene photographs may enable trace soil on clothing and possibly even shoe and tyre treads to be compared by Munsell colour. The same colour standard, such as the white scale bar used in this paper, would be required to allow photographs taken under a variety of lighting conditions to be compared using image processing software. This new method of analysing the colour of trace soil on fabric could enable crime scene evidence to be accurately analysed for the full range of 450 different standard Munsell colour chips, even when a spectrophotometer is not available. Image processing of digital trace soil photos may only be used as a preliminary step to compare and contrast different soil evidence before more expensive and time-consuming analytical testing is undertaken; such as XRD analysis of a soil's mineralogy. But this initial step may mean that vital forensic soil evidence is not completely ignored, as often happens, because the funds or expertise in more expensive analytical techniques are not available.

Once the image processing software was programmed, the analysis of each digital photograph took only 2 minutes for quantifiable numerical data to be produced. Simple Excel graphs then made comparison of the different soil transfer experiments very easy to comprehend.

A valuable outcome was the use of image processing software to produce Rose diagrams that plotted the directionality of soil transferred onto fabric. All digital photographs were taken of soil transfer patterns, with the direction of movement running horizontally from right to left. This would aid recognition of soil transfer patterns that were being documented for the very first time. This resulted in digital photographs with all soil 'trail' patterns running horizontally. Rose diagrams accordingly indicated strong uni-modal directionality; even with minimal trace soil transferred. There was also a trend for dry soil particles to be 'dammed' against the perpendicular middle seam during the dragging experiments; creating a more bi-modal directionality in these Rose diagrams.

Rose diagrams provided a quick, simple and cheap pictorial record of numerical data analysis of directionality of soil transferred to fabric. By combining image processing with Rose diagram software, this method could assist forensic investigators understand the circumstances behind fabric making contact with a soil surface. This method may also be used to gain the acceptance of these particular circumstances from a judge or jury, beyond reasonable doubt, in a court of law.

Combining image processing with rose diagrams objectively proved directional patterns recognised by naked eye could also be identified by computer software. The current forensic soil techniques utilising light microscopy, XRD and Scanning Electron Microscopy (Pelton 1995, 1998), could include image processing of trace soil patterns on clothing or other fabrics. The standardised objectivity achieved by combining these techniques, could not only assist forensic investigators understand the circumstances behind fabric making contact with a soil surface, but gain acceptance of this evidence beyond reasonable doubt in a court of law.

In future papers, the authors intend to use image processing software to analyse soil transfer patterns produced by different methods of transfer; including placing weighted fabric on a soil surface, as well as placing unweighted, randomly folded fabric on a soil surface for a set time.

7.6 How soil transfer patterns on clothing can assist police forensic officers to interpret soil evidence at a crime scene

At a crime scene, the tell-tale characteristics of whether trace soil was wet or dry when initially transferred to clothing, may be used to discover a 'window of opportunity' for when the soil was transferred. Using meteorological records corresponding to the date (and preferably time) of the crime, will help confirm trace soil evidence indicating soil was either wet or dry when initially transferred. If trace soil evidence seems to contradict the weather record, this may indicate that more than one location was used during the perpetration of the crime.

Other dry soil locations to consider would include a shed, a bus shelter or the inside of a vehicle. Other wet soil locations to consider would include soil surface areas with such bad drainage that water is unable to disperse; including areas paved with concrete or bricks, a riverbank, an open drain or irrigated paddock.

7.7 Loose trace soil evidence on clothing and the need to photographic soil transfer patterns *in situ*

From analyses of the eighty-four (84) soil transfer experiments undertaken, it soon became apparent that any loose soil would not remain *in situ* given the slightest movement of the clothing. Great care had to be taken to gently and quickly turn the tested bra upright so as to retain on the bra as much trace soil as possible. Digital photographs were then taken of the trace soil patterns *in situ* in the laboratory; followed by analysis using light microscopy. Just walking to the adjacent microscopy room would generate movement and loss of the loose soil particles.

Thus, the most pristine record of the trace soil transferred and soil transfer patterns produced, were detailed photographs taken using a basic digital camera at the testing site. Once morphological analyses were completed, the fabric surface was kept as level and stable as possible whilst removing the bra from the 2kg weight; before being stored horizontally in a plastic clip-lock bag. Despite all these efforts, once the fabric was removed from the weight, the intricate details of each soil transfer pattern were lost. Photos and photomicroscopy (whilst the 2kg weight was still in situ) then provided the only complete record of each transfer pattern obtained.

The delicate and impermanent nature of soil transfer patterns is dependent upon the soil texture, mineralogy and moisture content, which indicates that this type of forensic soil evidence will not survive the robust forensic testing of trace soil currently practised in most Police forensic laboratories.

The research conducted in this paper suggests that the circumstances behind soil making contact with fabric at a crime scene can be better understood by retaining a pristine method of the soil transference pattern recorded on the fabric. When soil evidence is scraped or shaken off clothing for XRD analysis, or the fabric is actually cut up, valuable soil evidence can be irreparably destroyed in the process. For this new method of soil forensic science to be of full use in a court of law, detailed photographs must be taken on site; preferably before the victim is moved or clothing removed.

8. CONCLUSIONS

Laboratory STEs used the transfer method of dragging weighted clothing (bras) across wet and dry RTBG soils. Digital photography taken immediately after each STE provided a pristine record of soil transference patterns on clothing fabric before each bra was removed from the stabilising 2kg weight.

In eighty-four (84) soil transfer experiments undertaken on seven anthropogenic soil samples from the RTBG, eight transference patterns were identified by the naked eye, and confirmed by light microscopy. However, only the first six patterns were seen with 100% consistency in soil transferred onto each bra.

Soils were further categorised by compositional characteristics into six different soil types, both natural and anthropogenic. Soil transfer patterns were then investigated to determine the most influential factors that characterised the composition of the source soil. Quantity of soil transferred was dependant primarily on soil type, moisture content, particle size and mineralogy. Dark organic loamy-sand textured soil provided the most abundant and easy to identify soil transfer patterns against the white bra fabric. Gravel-rich, matrix-poor and low-clay soils transferred the lowest quantity of soil to fabric.

Image processing software proved valuable in providing quantifiable graphical presentations on:
(i) quantity of soil transferred, (ii) percentage of individual soil objects and aggregates transferred and (iii) direction patterns. (iv) the ability to identify and compare Munsell colours.

Dragging was the only transfer method tested. Future experiments will need to be conducted using different transfer methods to identify whether any soil transfer patterns on fabric are so unique that they can be used to indisputably identify a specific transfer method.

XRD results indicated the mineral composition, which comprised thirteen (13) minerals of the bulk soil samples as being typical loamy to clayey Tasmanian soils. NDIR identified carbon levels as being up to 3.10% on the gravel-rich soils, 14% for the Rose garden bed and 22.8% in natural soil. No Sulfur-bearing species were identified.

Image processing software proved valuable in providing in-depth quantifiable numerical data on: (i) quantity of soil transferred, (ii) percentage of individual soil objects and aggregates transferred in relation to soil type and (iii) direction patterns.

There is tremendous potential for image processing analysis to accurately identify and compare the Munsell colour of trace soil evidence on fabric without requiring a spectrophotometer.

The most forensically valuable data involved a specific, reproducible Munsell soil colour range for trace soil evidence on fabric that shared the same location; as well as the directionality of soil transferred plotted as Rose diagrams.

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10. REFERENCES

Aardahl, K (2003) Evidential value of glitter particle trace evidence. National University.

Aardahl, K, Kirkowski, S, Blackledge, R (2005) A target glitter study. *Sci Justice* **45**, 7-12.

Allaby, A, Allaby, M (1999) 'A Dictionary of Earth Sciences.' (Oxford University Press:

ASRIS (Australian Soil Resources Information System) (2013) 'Maps, ASRIS (Australian Soil Resources Information System), [Database].' Available at www.asris.csiro.au [Accessed May 6].

Bull, P, Morgan, R, Sagovsky, A, Hughes, G (2006a) The transfer and persistence of trace particulates: Experimental studies using clothing fabrics. *Sci Justice* **46**, 185-195.

Bull, P, Parker, A, Morgan, R (2006b) The forensic analysis of soils and sediment taken from the cast of a footprint. *Forensic Sci Int* **162**, 6-12.

Chung, F (1975) Quantitative Interpretation of X-Ray Diffraction patterns of mixtures. III. Simultaneous determination of a set of reference Intensities. *J. Applied Crystallography* **8**, 17-19.

Fitzpatrick, R (2008) Nature, distribution and origin of soil materials in the forensic comparison of soils. In 'Soil analysis in forensic taphonomy: chemical and biological effects of buried human remains.' (Eds M Tibbett, D Carter.) pp. 1-28. (CRC Press: Doca Raton, FL)

Fitzpatrick, R, 2011. The value of soil in criminal investigations. Soil Forensics profile Newsletter. The Australian Society for Soil Science Inc, Victoria. 5-6.

Fitzpatrick, R, 2012. Forensic earth science: Getting the dirt on crime. e-Science. Faculty of Sciences, The University of Adelaide, Adelaide. 5-11.

Fitzpatrick, R (2013a) Demands on soil calssification and soil survey strategies: Special-purpose soil classification systems for local practical use. In 'Developments in soil classiification, land use planning and policy implications: Innovative thinking of soil inventory for land use planning and management of land resources.' (Eds S Shahid, F Taha, M Abdelfattah.) pp. 51-83. (Springer Science+Business Media Dordrecht: Netherlands)

Fitzpatrick, R (2013b) Soil: Forensic Analysis. In 'Wiley Encyclopedia of Forensic Science.' (Eds A Jamieson, A Moenssens.) Chichester, West Sussex)

Fitzpatrick, R, Raven, M (2012a) How Pedology and mineralogy helped solve a double murder case: Using forensics to inspire future generations of soil scientists. *Soil Horizons* **53**, 14-29.

Fitzpatrick, R, Raven, M (2012b) The State of Western Australia v. Lloyd Patrick Rayney Trail: Request for supplementary statement relating to extraction of particulate material from bra. Centre for Australian Forensic Soil Science.

Fitzpatrick, R, Raven, M (2013) Soils. In 'Encyclopedia of Forensic Sciences.' (Eds J Siegel, P Saukko.) pp. 206-212. (Academic Press: Waltham)

Fitzpatrick, R, Raven, M, Forrester, S (2009) A systematic approach to soil forensics: Criminal case studies involving transference from crime scene to forensic evidence. In 'Criminal and Environmental Soil Forensics.' (Eds K Ritz, L Dawson, D Miller.) pp. 105-127. (Springer Netherlands: Netherlands)

Fitzpatrick, R, Raven, M, Self, P (2011) Detailed mineralogical characterization of small brick and soil fragments (<0.5mm diameter) by Synchrotron X-ray diffraction analyses for further forensic comparisons relating to Operation Dargan.

Fitzpatrick, R, Raven, M, Self, P (2012a) Sampling and analyses of 18 soil samples relating to a murder investigation by WA Police named Operation ONXY Final Report. Centre for Australian Forensic Soil Science, Adelaide.

Fitzpatrick, R, Raven, M, Self, P (2012b) Soil as significant evidence in a sexual assault case. In 'Proceedings of the 5th Joint Australian and New Zealand Soil Science Conference: Soil solutions for diverse landscapes.' (Eds L Burkitt, L Sparrow.) (Australian Society of Soil Science Inc: Hobart)

Fitzpatrick, R, Raven, M, Self, P RJ Gilkes (Ed.) (2014) 'Clay mineralogy as significant evidence in 4 murder investigations involving a wide range of earth materials from Perth, Adelaide, Melbourne and Sydney, Proceedings 23rd Australian Clay Minerals Society Conference.' Perth, 3-5 February, 2014. (Australian Clay Minerals Society

Galbraith, J (2012) Rationale for proposed changes to Soil Taxonomy concerning the International Committee for Anthropogenic Soils. *Soil Horizons* **March-April**, 2-6.

Hergt, J, Chappell, B, McCulloch, M, McDougall, I, Chivas, A (1989) Geochemical and isotopic constraints on the origin of the Jurassic Dolerites of Tasmania. *Journal of Petrology* **30**, 841-883.

Hicks, T, Vanina, R, Margot, P (1996) Transfer and persistence of glass fragments on garments. *Sci Justice* **36**, 101-107.

Holcombe, R (2011) 'GEOrient.' (School of Earth Sciences, University of Queensland: Queensland, Australia)

Isbell, R (2002) 'The Australian soil classification.' (CSIRO Publishing: Melbourne)

Klug, H, Alexander, L (1954) 'X-Ray diffraction procedures for polycrystalline and amorphous materials.' (Wiley: New York)

Leaman, D, 1976. Hobart. Geological Atlas 1:50 000 series. Geological Survey Tasmania, Tasmania, Australia. Sheet 82 (8312S).

Locard, E (1930) Analyses of dust traces parts I, II and III. *American Journal of Police Science.* **1**, 276-98, 401-18, 496-514.

Maniar, P, Cooke, G (1987) Modal analyses of granitoids by qualitative X-ray diffraction. *American Mineralogist* **72**, 433-437.

Martin, B, 2012a. Judgement summary: The State of Western Australia v. Rayney. [No 3]. WASC, 404 (INS 83 of 2011): 1-13.

Martin, B, 2012b. The State of Western Australia v. Rayney. [No 3]. WASC, 404: 1-369.

McDermott, S (2013) Trace evidence: Transfer, persistence adn value. In 'Encyclopedia of forensic sciences.' (Ed. J Siegel.) (Academic press: Waltham)

McDonald, R, Isbell, R (2009) 'Soil profile.' (CSIRO Publishing: Melbourne)

McKenzie, N, Jacquier, D, Isbell, R, Brown, K (2004) 'Australian soils and landscapes: an illustrated compendium.' (CSIRO Publishing: Australia)

Morgan, R, Bull, P (2007) Forensic geosciences and crime detection: Identification, interpretation and presentation in forensic geoscience. *Minerva Medicolegale* **127**, 73-89.

Morgan, R, Cohen, J, McGookin, I, Murly-Gotto, J, O'Connor, R, Muress, S, Freudiger-Bonzon, J, Bull, P (2009) The relevance of the evolution of experimental studies for the interpretation and evaluation of some trace physical evidence. *Sci Justice* **49**, 277-285.

Munsell_Color_Company (2009) 'Munsell soil color book.' (Munsell Color X-rite: Michigan)

Murray, K, Fitzpatrick, R, Doyle, R (2012) Development of soil forensic methods databases from targeted locations in Tasmania to assist police. In 'Proceedings of the 5th Joint Australian and New Zealand Soil Science Conference: Soil solutions for diverse landscapes.' (Eds L Burkitt, L Sparrow.) pp. 661. (Australian Society of Soil Science Inc: Hobart)

Murray, R (2011) 'Evidence from the earth: Forensic geology and criminal investigation.' (Mountain Press Publishing: Missoula, MT)

Pelton, W (1995) Distinguishing the cause of textile fibre damage using the scanning electron microscope (SEM). *J Forensic Sci* **40**, 874–882.

Pelton, W (1998) Use of SEM in textile forensic work. In 'Atlas of Fibre Fracture and Damage to Textiles.' (Eds J Hearle, B Lomas, W Cooke.) pp. 406–415. (Woodhead Publishing Limited: Cambridge)

Pounds, C, Smalldon, K (1975a) The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. III: A preliminary investigation of the mechanisms involved. *Journal Forensic Science Soc.* **15**, 197-207.

Pounds, C, Smalldon, K (1975b) The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part I: fibre transference. *Journal Forensic Sci Society* **15**, 17-27.

Pounds, C, Smalldon, K (1975c) The transfer of fibres between clothing materials during simulated contacts and their persistence during wear. Part II: fibre persistence. *Journal Forensic Sci Soc.* **15**, 29-37.

Pye, K (2007) 'Geological and soil evidence: Forensic applications.' (CRC Press: Boca Raton, Florida)

Reid, D, 2012. Unpublished statement from RTBG Horticultural Coordinator, regarding the establishment of the gardens and the heritage-listed convict-built Eardley Wilmot brick wall.

Roux, C, Robertson, J (2013) Fibers. In 'Encyclopedia of forensic sciences.' (Ed. J Siegel.) (Academic Press: Waltham)

Ruffell, A, McKinley, J (2008) 'Geoforensics.' (John Wiley & Sons, Ltd.: Chichester)

Rumney, P (2006) False allegations of rape. *Cambridge Law Journal* **65**, 128-158.

Schoeneberger, P, Wysocki, D, Benham, E, Broderson, W (2002) 'Field book for describing and sampling soils.' (USDA-NRCS, National Soil Survey Center: Lincoln, NE)

Soil_Survey_Staff (2014) 'Keys to Soil Taxonomy.' (United States Department of Agriculture, Natural Resources Conservation Service: Washington)

Sugita, R, Marumo, Y (1996) Validity of color examination for forensic soil identification. *Forensic Sci International* **83**, 201-210.

Sun, S, Nesbitt, R (1978) Geochemical regularities and genetic significance of ophiolitic basalts. *Geology* **6**, 689-693.

Taupin, J (2000) Clothing damage analysis and the phenomenon of the false sexual assault. *Journal of Forensic Sciences* **45**, 568-572.

Weaver, C (Ed.) (1990) 'Clays, muds and shales.' In 'Developments in sedimentology'. (Elsevier: Amsterdam)

World_Reference_Base (2014) World Reference Base (WRB) for Soil Resources 2014: A framework for international classification, correlation and communication. Food and Agriculture Organization of the United Nations Rome, Rome.

11. Appendix 1 – Soil Transference patterns identified in STEs using the transfer method of dragging

SOIL TRANSFERENCE PATTERNS:			Bra-strap &/or cup		Bra-strap only					Cup only
Soil Sample no.	Location Description	Run	Soil trails strap/cup	Elongated fragments aligned	Strap edge soil build-up	Buckle soil build-up	Fluffy seam soil build-up	Dry: Dusting of soil evenly over buckle	Wet: buckle clean &/or muddy clumps	Cup seam soil build-up
110.5.1	Rose	Dry 1	√	√	√	√	√	√	N/A	√
	Garden	Dry 2	√	Strap only	√	√		√	N/A	√
	Path	Dry 3	√	√	√	√	√	√	N/A	√
	(<2mm	Wet 1	√		√	√		N/A	√	√
	Texture	Wet 2	√	√	√	√		N/A	√	√
	= LS)	Wet 3	√	√	√	√		N/A	√	√
% occurrence of patterns		Dry	100%	83.3%	100%	100%	66.6%	100%	N/A	100%
in 110.5.1		Wet	100%	66.6%	100%	100%	0%	N/A	100%	100%
110.6.1	Rose	Dry 1	√	√	√	√	√	√	N/A	√
	Garden	Dry 2	√	√	√	√	√	√	N/A	√
	Path	Dry 3	√	√	√	√		√	N/A	√
	near wall	Wet 1	√		√	√		N/A	√	√
	(<2mm	Wet 2	√	√	√	√	√	N/A	√	√
	Tex = S)	Wet 3	√	√	√	√		N/A	√	√
% occurrence of patterns		Dry	100%	100%	100%	100%	66.6%	100%	N/A	100%
in 110.6.1		Wet	100%	66.6%	100%	100%	33%	N/A	100%	100%
110.6.2	Brick	Dry 1	√		√	√		√	N/A	√
	fragments	Dry 2	√	Cup only	√	√	√	√	N/A	√
		Dry 3	√		√	√		√	N/A	√
	(<2mm	Wet 1	√	Cup only	√	√		N/A	√	√
	Texture	Wet 2	√	√	√	√		N/A	√	√
	= Brick)	Wet 3	√		√	√		N/A	√	√
% occurrence of patterns		Dry	100%	16.6%	100%	100%	33.3%	100%	N/A	100%
in 110.6.2		Wet	100%	50%	100%	100%	0%	N/A	100%	100%
110.7.1	Rose	Dry 1	√	√	√	√	√	√	N/A	√
	Garden	Dry 2	√	√	√	√		√	N/A	√
	Bed	Dry 3	√	√	√	√		√	N/A	√
	(<2mm	Wet 1	√	√	√	√		N/A	√	√
	Texture	Wet 2	√	√	√	√	√	N/A	√	√
	= LS)	Wet 3	√	√	√	√		N/A	√	√
% occurrence of patterns		Dry	100%	100%	100%	100%	33.30%	100%	N/A	100%
in 110.7.1		Wet	100%	100%	100%	100%	33.30%	N/A	100%	100%
110.8.1	Japanese	Dry 1	√	Cup only	√	√		√	N/A	√
	Garden	Dry 2	√		√	√	√	√	N/A	√
	Path	Dry 3	√		√	√		√	N/A	√
	(<2mm	Wet 1	√	Strap only	√	√		N/A	√	√
	Texture	Wet 2	√		√	√		N/A	√	√
	= LS)	Wet 3	√	Strap only	√	√		N/A	√	√
% occurrence of patterns		Dry	100%	16.6%	100%	100%	33.3%	100%	N/A	100%
in 110.8.1		Wet	100%	33.3%	100%	100%	0%	N/A	100%	100%

Appendix 1 continued…

SOIL TRANSFERENCE PATTERNS:			Bra-strap &/or cup		Bra-strap only					Cup only
Soil Sample no.	Location Description	Run	Soil trails strap/cup	Elongated fragments aligned	Strap edge soil build-up	Buckle soil build-up	Fluffy seam soil build-up	Dry: Dusting of soil evenly over buckle	Wet: buckle clean &/or muddy clumps	Cup seam soil build-up
110.9.1	Natural Soil (Leaf litter)	Dry 1	√		√	√		√	N/A	√
		Dry 2	√	√	√	√		√	N/A	√
		Dry 3	√		√	√		√	N/A	√
		Wet 1	√	Strap only	√	√		N/A	√	√
		Wet 2	√		√	√	√	N/A	√	√
		Wet 3	√	√	√	√	√	N/A	√	√
% occurrence of patterns in 110.9.1		Dry	100%	33.3%	100%	100%	0%	100%	N/A	100%
		Wet	100%	50%	100%	100%	66.6%	N/A	100%	100%
110.9.2	Natural Soil (<2mm Texture = LS)	Dry 1	√	√	√	√	√	√	N/A	√
		Dry 2	√	√	√	√	√	√	N/A	√
		Dry 3	√	√	√	√	√	√	N/A	√
		Wet 1	√	√	√	√		N/A	√	√
		Wet 2	√	√	√	√	√	N/A	√	√
		Wet 3	√	√	√	√	√	N/A	√	√
% occurrence of patterns in 110.9.2		Dry	100%	100%	100%	100%	100%	100%	N/A	100%
		Wet	100%	100%	100%	100%	100%	N/A	100%	100%
TOTAL AVERAGE % occurrence of patterns		Dry	100%	64.2%	100%	100%	47.6%	100%	N/A	100%
		Wet	100%	66.6%	100%	100%	28.6%	N/A	100%	100%

KEY:

√ = pattern occurs on both bra-strap and cup

N/A = Not applicable

Dry run: soil has been air-dried in soil tray for a month

Wet run: soil has been sprayed with distilled water until colour has changed and surface is wet and glistening.

Soil trails strap/cup: Soil trail appears as a brownish streak parallel to direction of movement; or as a trail of fine (<2mm) rounded particles, aligned parallel with the direction of movement

Elongate fragments aligned: One or more elongate particles are aligned with the direction of movement

Strap edge soil build-up: Soil has been transferred along either edge of the bra-strap

Buckle soil build-up: Soil has transferred over the top fabric on buckle and is absent directly behind back metal buckle-bar

Fluffy seam soil build-up: Soil accumulated on fluffy raised seam at top/bottom of bra-strap in a greater quantity/mm Than seen on smoothly-woven strap

Dry: Dusting soil evenly on buckle: During a dry run, soil has been dusted evenly over entire metal buckle

Wet: buckle clean &/or muddy clumps: During a wet run, the buckle is clean, except for individual wet muddy clumps of soil (2mm-5mm)

Cup seam soil build-up: Soil has accumulated across raised cup seam; and behind this seam, there is less soil than in front.

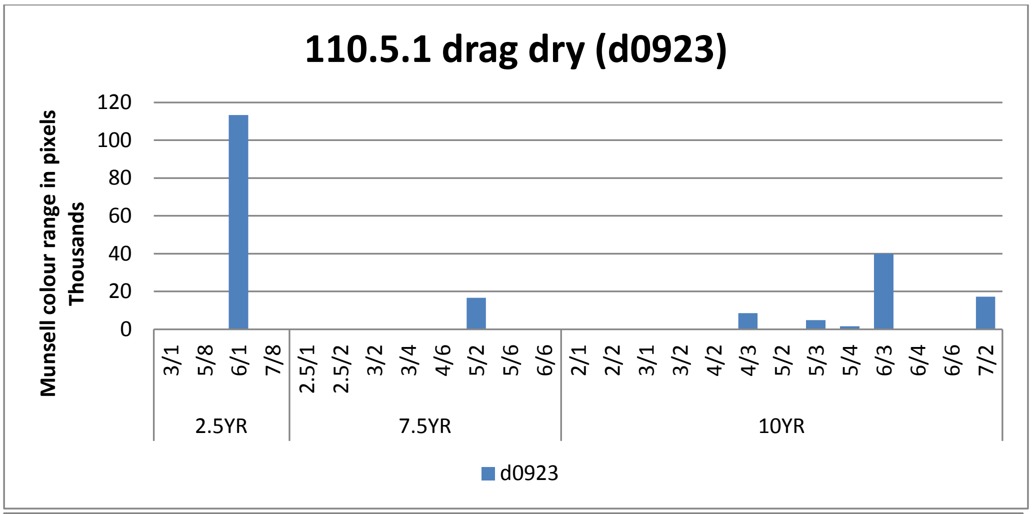
12. APPENDIX 2 – Image processing numerical data showing Munsell colour range of soil samples shown as area in pixels

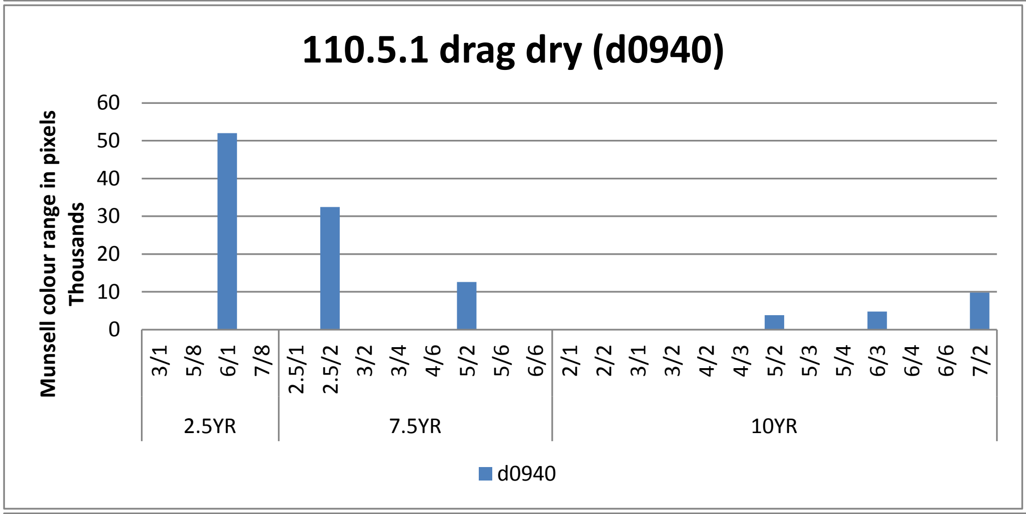
Soil Sample no.	Soil Transfer Method	Soil moisture content	Digital Photo no.	Munsell colour range (Area of each colour in pixels)											
				2.5YR				7.5YR							
				3/1	5/8	6/1	7/8	2.5/1	2.5/2	3/2	3/4	4/6	5/2	5/6	6/6
110.5.1	drag	dry	d0923	0	0	113331	0	0	0	0	0	0	16651	0	0
110.5.1	drag	dry	d0940	0	0	52037	0	0	32448	0	0	0	12597	0	0
110.5.1	drag	dry	d0951	0	0	38887	0	0	5529	0	0	0	4904	0	0
110.5.1	drag	wet	d0960	0	0	65695	0	0	25942	0	0	0	5576	0	0
110.5.1	drag	wet	d0975	0	0	99924	0	0	25270	0	17954	8807	8261	0	0
110.5.1	drag	wet	d0988	0	0	102981	0	0	46754	0	0	6223	23886	0	0
110.6.1	drag	dry	d1146	32	0	43993	0	0	107462	0	0	0	6899	0	0
110.6.1	drag	dry	d1172	0	125	79130	0	0	5010	0	0	0	7656	0	0
110.6.1	drag	dry	d1193	0	0	47210	0	0	45549	0	16994	0	2969	0	0
110.6.1	drag	wet	d1220	0	0	85460	0	0	0	0	0	16201	15990	0	0
110.6.1	drag	wet	d1241	0	0	68460	0	0	5688	0	19828	14486	23145	0	0
110.6.1	drag	wet	d1260	0	0	84324	0	0	20232	0	0	0	7040	0	0
110.6.2	drag	dry	d1840	0	263	121548	241	0	22703	0	0	5074	0	0	41318
110.6.2	drag	dry	d1865	0	263	94715	0	0	18640	0	0	0	5234	0	10642
110.6.2	drag	dry	d1889	0	0	62224	27	0	0	0	0	0	0	0	0
110.6.2	drag	wet	d1912	0	0	88272	40	0	11324	0	0	2324	0	9609	0
110.6.2	drag	wet	d1934	0	151	124520	956	0	53400	0	0	0	4812	0	8766
110.6.2	drag	wet	d1958	0	239	115282	696	0	57974	0	0	0	17400	0	20950
110.7.1	drag	dry	d1280	0	0	80078	0	0	2474518	0	365845	3429	668399	0	0
110.7.1	drag	dry	d1298	8	0	114874	34	0	1086558	172143	464924	5129	283960	0	0
110.7.1	drag	dry	d1323	1	0	71086	0	2298	736083	202271	777067	10450	296127	0	11068
110.7.1	drag	wet	d1346	0	0	88409	0	1935	254862	195497	457550	0	59681	0	0
110.7.1	drag	wet	d1368	0	0	77759	0	11322	325412	756886	2038868	29978	161194	0	0
110.7.1	drag	wet	d1388	0	0	87639	0	2322	25364	762162	1997056	42271	84291	0	0
110.8.1	drag	dry	d1413	0	0	52053	0	0	24332	0	42000	2353	2424	0	0
110.8.1	drag	dry	d1430	0	0	47770	0	0	40413	0	17062	0	5197	0	0
110.8.1	drag	dry	d1450	0	0	35087	0	0	0	0	0	0	0	0	0
110.8.1	drag	wet	d1468	0	0	36312	0	0	0	0	0	0	0	0	0
110.8.1	drag	wet	d1488	0	0	22148	0	0	43766	0	0	0	12858	0	0
110.8.1	drag	wet	d1509	0	0	106176	0	0	81552	0	0	0	15607	0	0
110.9.1	drag	dry	d1725	0	0	75649	0	0	135416	0	54153	0	24213	0	0
110.9.1	drag	dry	d1747	0	0	37250	0	0	137791	0	0	0	11225	0	0
110.9.1	drag	dry	d1764	0	0	31107	52	0	69017	25883	33999	0	10610	0	0
110.9.1	drag	wet	d1780	0	121	21907	61	0	86930	25385	0	34629	5531	4913	0
110.9.1	drag	wet	d1798	0	0	53381	0	0	39241	0	0	0	13600	0	0
110.9.1	drag	wet	d1814	0	0	36713	0	0	101949	0	41138	0	21108	0	0
110.9.2	drag	dry	d1532	126	122	18569	0	3956	471883	422358	875503	0	170797	0	0
110.9.2	drag	dry	d1563	0	0	129008	0	0	338745	71727	488347	2029	67421	0	0
110.9.2	drag	dry	d1600	0	0	109028	0	0	339312	123250	644913	1905	97453	0	0
110.9.2	drag	wet	d1631	47	0	159346	0	17565	1231489	1092405	2521171	0	318993	0	0
110.9.2	drag	wet	d1664	0	0	145622	0	28404	583207	1808232	2896262	9058	345897	0	0
110.9.2	drag	wet	d1697	0	0	172117	0	10325	284132	1194127	3138044	1614	409613	0	0

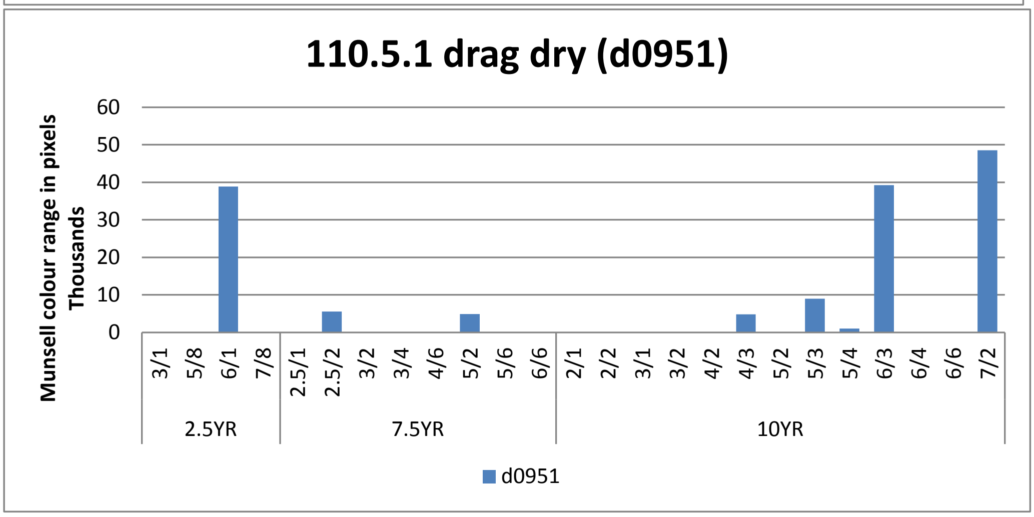
Appendix 2 continued…

Soil Sample no.	Soil Transfer Method	Soil moisture content	Digital Photo no.	Munsell colour range (Area of each colour in pixels)												
				10YR												
				2/1	2/2	3/1	3/2	4/2	4/3	5/2	5/3	5/4	6/3	6/4	6/6	7/2
110.5.1	drag	dry	d0923	0	0	0	0	0	8594	0	4871	1627	39965	0	0	17304
110.5.1	drag	dry	d0940	0	0	0	0	0	0	3841	0	0	4815	0	0	9821
110.5.1	drag	dry	d0951	0	0	0	0	0	4831	0	9009	1035	39216	0	0	48534
110.5.1	drag	wet	d0960	0	0	0	0	0	0	0	4497	2791	63258	0	0	9512
110.5.1	drag	wet	d0975	0	0	0	0	0	0	7999	18106	5807	84337	16872	0	123635
110.5.1	drag	wet	d0988	0	0	0	0	0	0	0	12735	1584	74571	812	0	108605
110.6.1	drag	dry	d1146	0	0	0	0	0	0	0	3062	0	4835	0	0	0
110.6.1	drag	dry	d1172	0	0	0	0	0	3260	0	0	0	17930	0	0	5596
110.6.1	drag	dry	d1193	0	0	0	0	0	0	0	0	0	8737	0	0	4658
110.6.1	drag	wet	d1220	0	0	0	0	3188	1783	0	32993	8313	113309	6462	0	122005
110.6.1	drag	wet	d1241	0	0	0	0	0	0	0	17281	10333	128533	898	0	98707
110.6.1	drag	wet	d1260	0	0	0	0	0	0	0	9668	4356	21074	0	0	36990
110.6.2	drag	dry	d1840	0	0	0	0	0	0	0	6549	0	26724	0	0	24653
110.6.2	drag	dry	d1865	0	0	0	0	0	0	0	0	0	33694	0	0	14488
110.6.2	drag	dry	d1889	0	0	0	0	0	0	0	0	0	0	0	0	21427
110.6.2	drag	wet	d1912	0	0	0	0	0	0	0	0	0	23072	3213	0	36802
110.6.2	drag	wet	d1934	0	0	0	0	0	0	0	0	0	8815	0	0	35590
110.6.2	drag	wet	d1958	0	0	0	0	0	0	3641	0	0	25274	0	0	14064
110.7.1	drag	dry	d1280	0	0	0	0	215155	29892	61336	17698	1681	170577	0	0	47076
110.7.1	drag	dry	d1298	0	0	0	0	150695	40825	33776	38327	3750	177262	1656	0	106122
110.7.1	drag	dry	d1323	0	0	0	0	121451	55321	65694	21543	7876	233031	8183	0	163613
110.7.1	drag	wet	d1346	0	0	0	0	23446	18575	13111	6109	604	54799	0	0	20694
110.7.1	drag	wet	d1368	0	0	0	0	57862	130192	29053	104840	6854	370562	0	0	204645
110.7.1	drag	wet	d1388	0	0	0	0	7009	140584	8072	145026	26655	527096	3811	0	579963
110.8.1	drag	dry	d1413	0	0	0	0	3166	4573	0	0	0	9106	0	0	0
110.8.1	drag	dry	d1430	0	0	0	0	0	0	0	0	0	18860	0	0	20871
110.8.1	drag	dry	d1450	0	0	0	0	0	0	0	0	0	0	0	0	6083
110.8.1	drag	wet	d1468	0	0	0	0	0	0	0	0	0	0	0	0	6490
110.8.1	drag	wet	d1488	0	0	0	0	2787	0	7855	0	827	5028	0	0	0
110.8.1	drag	wet	d1509	0	0	0	0	0	0	3367	3310	0	10969	0	0	15361
110.9.1	drag	dry	d1725	0	0	0	0	0	1576	14968	7714	0	54195	0	0	49054
110.9.1	drag	dry	d1747	0	0	0	0	5669	5100	0	2820	1593	39016	0	0	32206
110.9.1	drag	dry	d1764	0	0	0	0	0	1398	3742	3994	1070	18416	4176	0	25480
110.9.1	drag	wet	d1780	0	0	0	0	3995	1353	3538	0	0	25784	0	0	13954
110.9.1	drag	wet	d1798	0	0	0	0	4235	1425	4162	0	0	65105	0	0	111153
110.9.1	drag	wet	d1814	0	0	0	0	5365	4042	10235	5478	0	47233	0	0	38878
110.9.2	drag	dry	d1532	0	0	0	0	118188	26494	51720	3523	0	30505	0	0	18937
110.9.2	drag	dry	d1563	0	0	0	0	35341	15433	50263	6043	575	78304	0	0	29579
110.9.2	drag	dry	d1600	0	0	0	0	40944	10172	67638	25990	2056	194771	0	0	117478
110.9.2	drag	wet	d1631	0	0	0	0	251492	117341	110215	46498	2582	373810	0	0	119050
110.9.2	drag	wet	d1664	0	0	0	0	173640	217797	48211	65892	14799	406602	0	0	204336
110.9.2	drag	wet	d1697	0	0	0	12385	119736	286754	39344	193941	21102	545406	0	0	391694

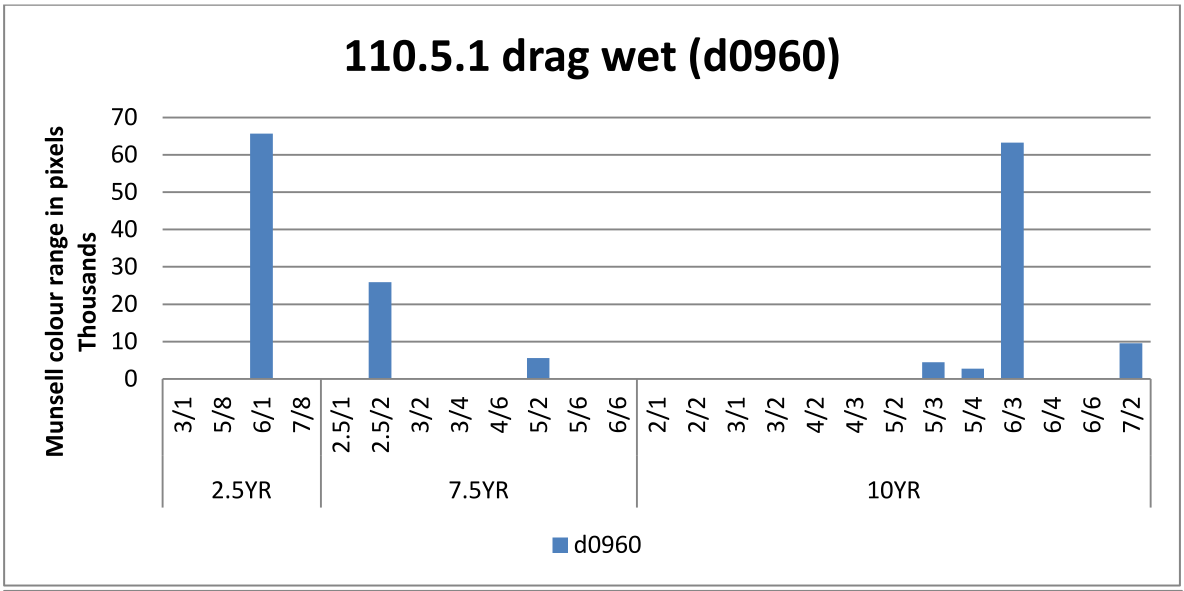
13. Appendix 3 – Graphs of Munsell colour range identified by image processing software for the digital photo taken of each soil sample

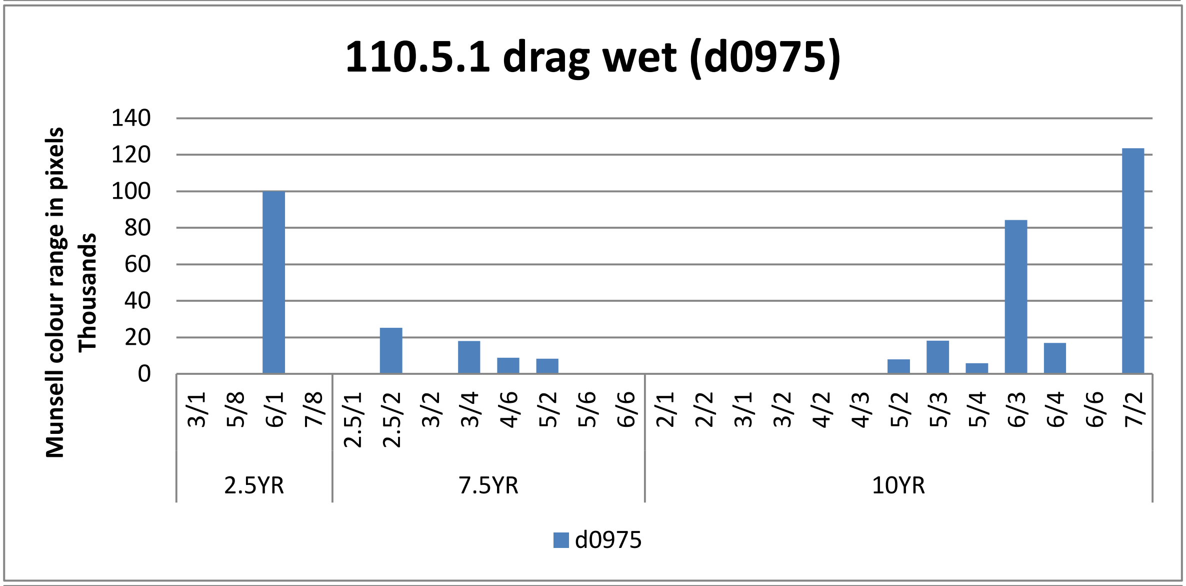


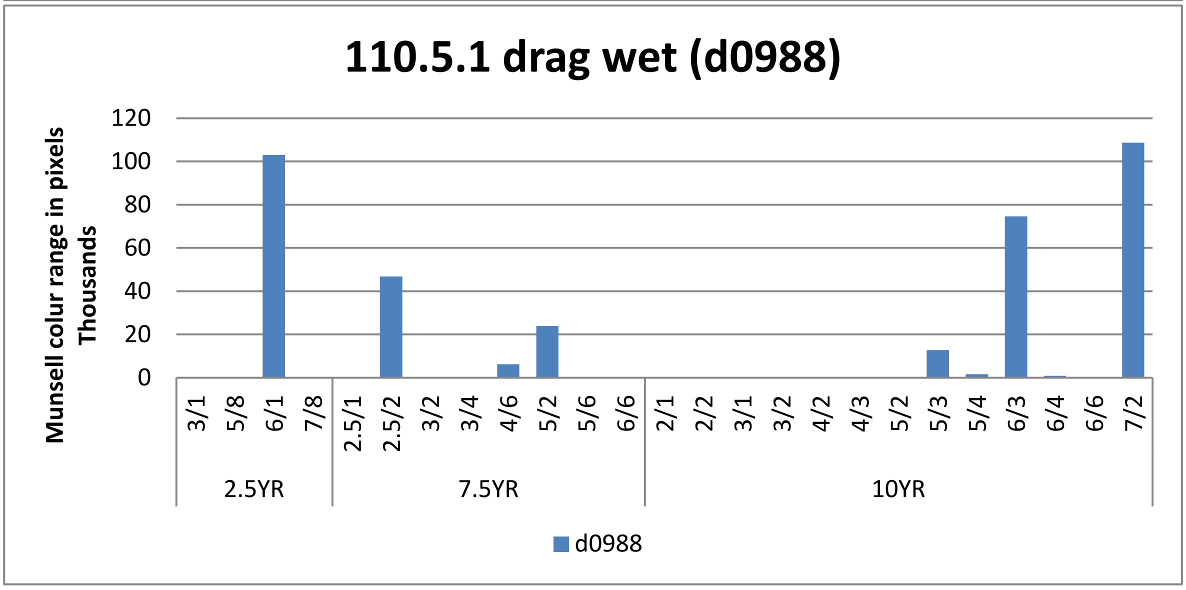




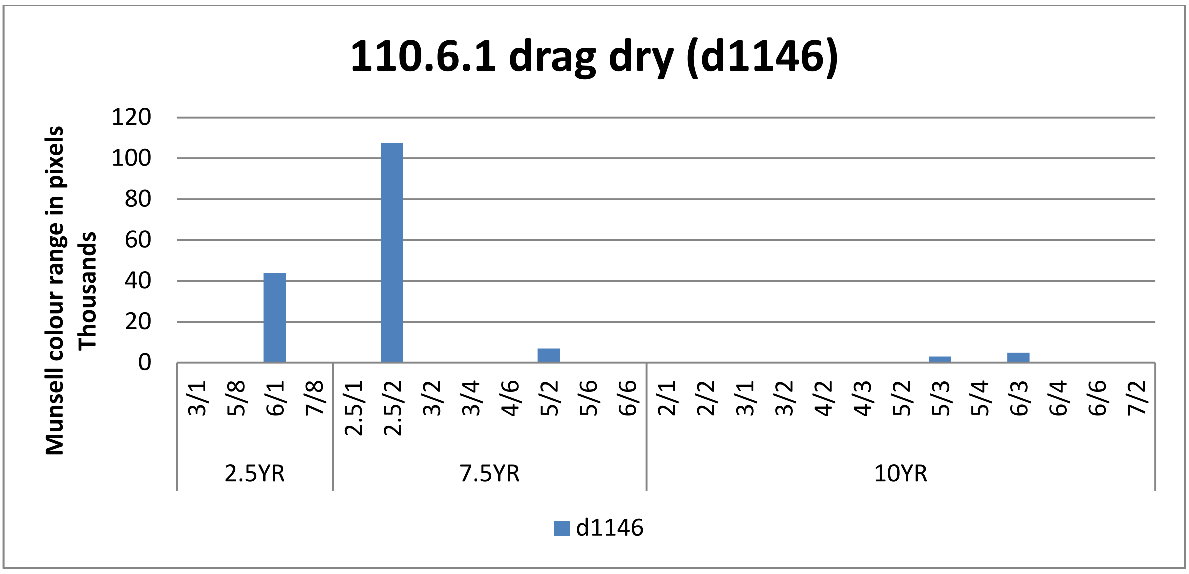
Appendix 3 continued...

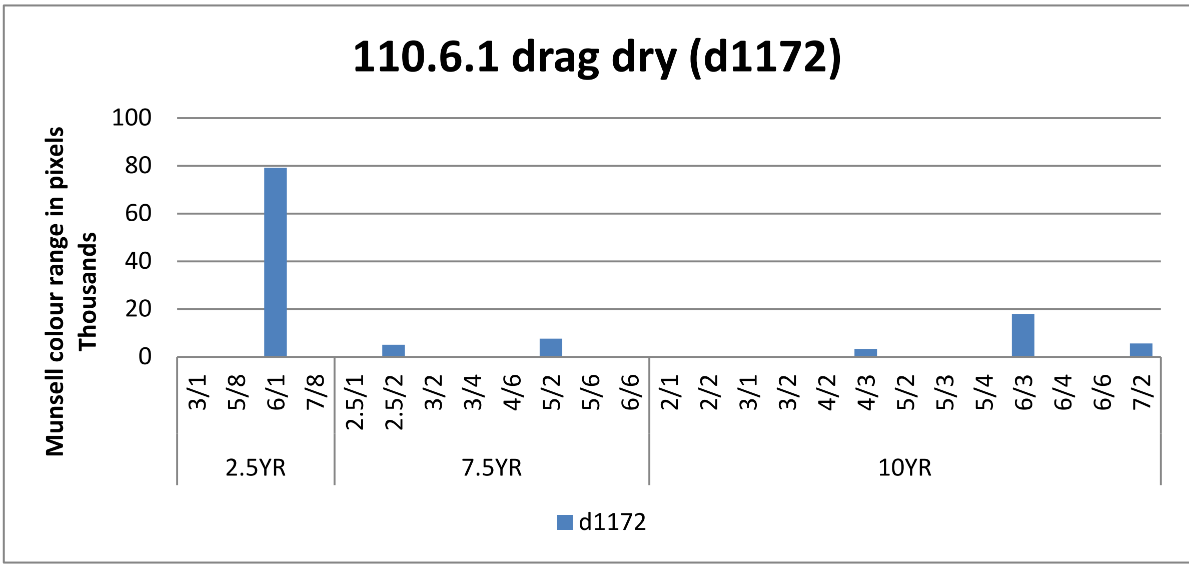


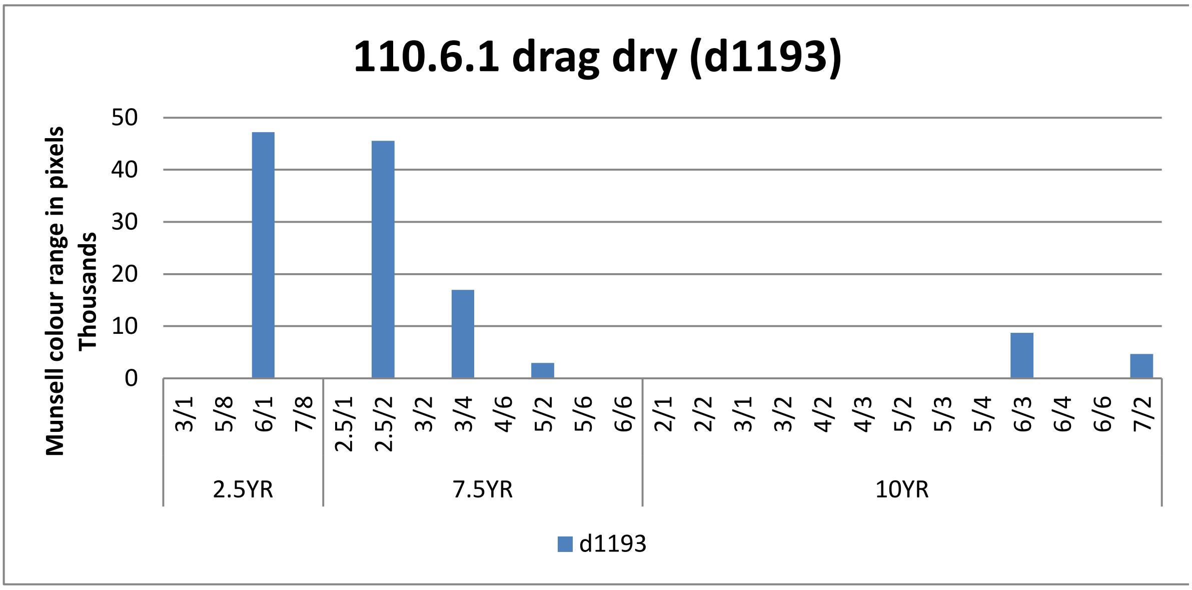




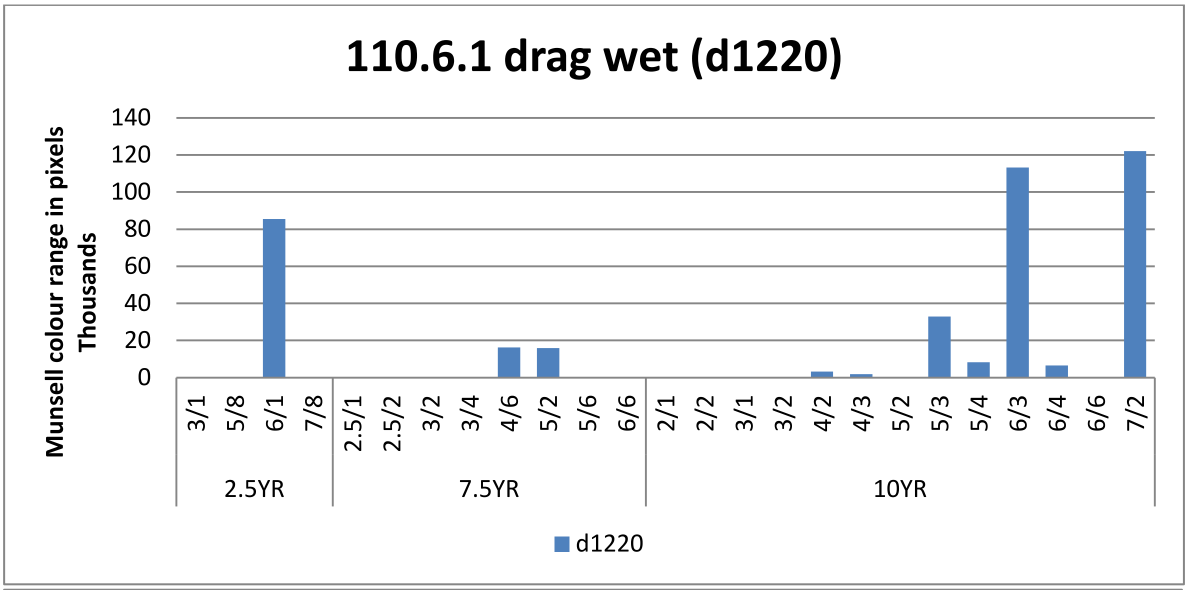
Appendix 3 continued...

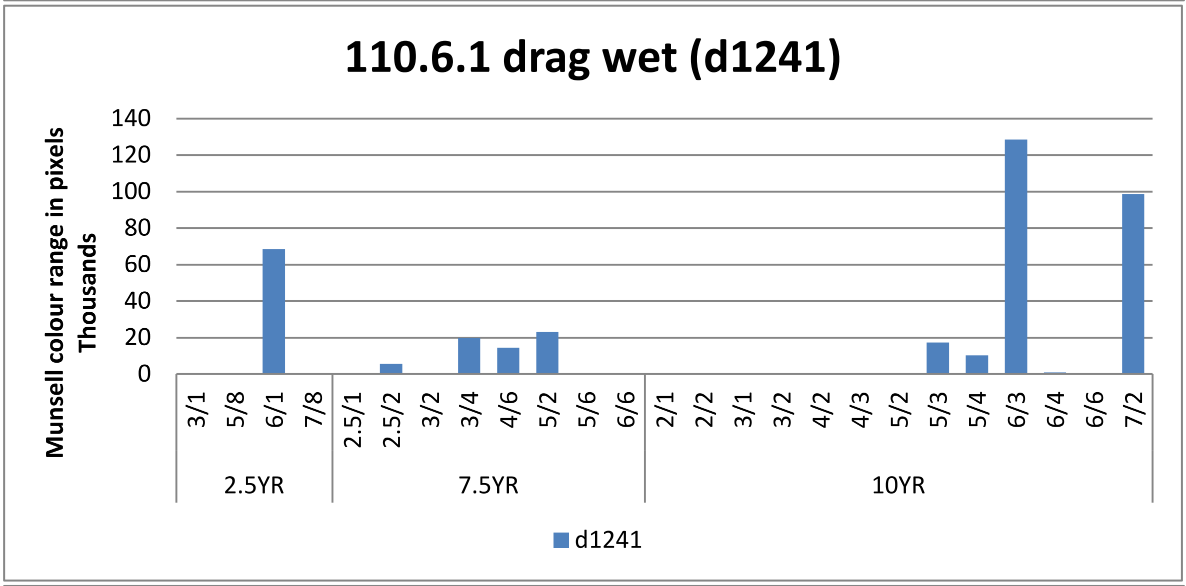


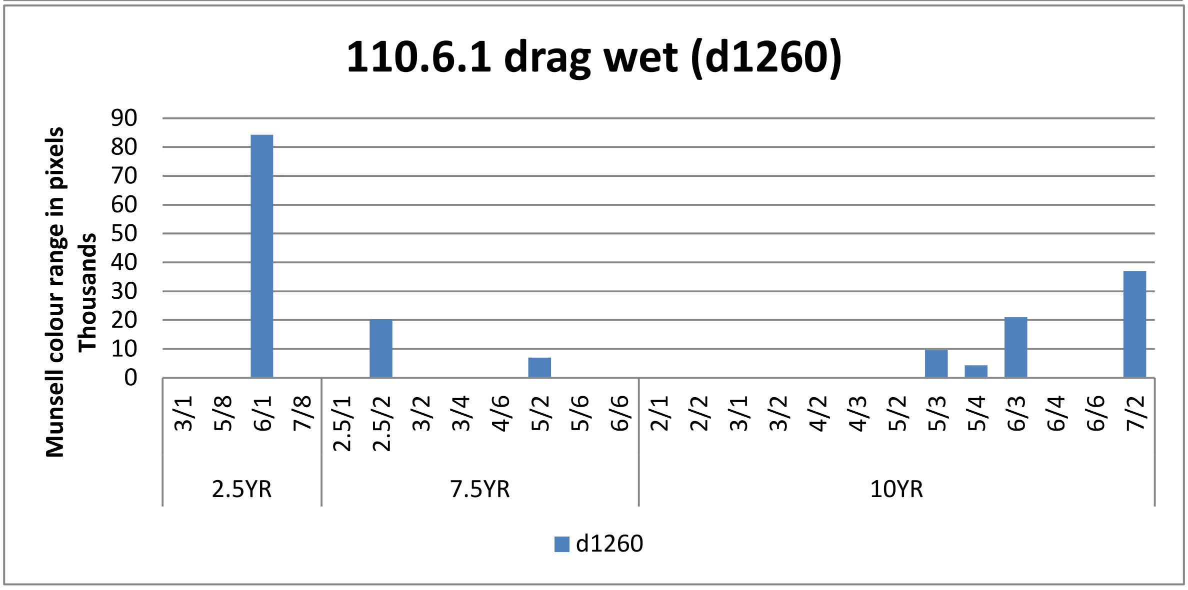




Appendix 3 continued...







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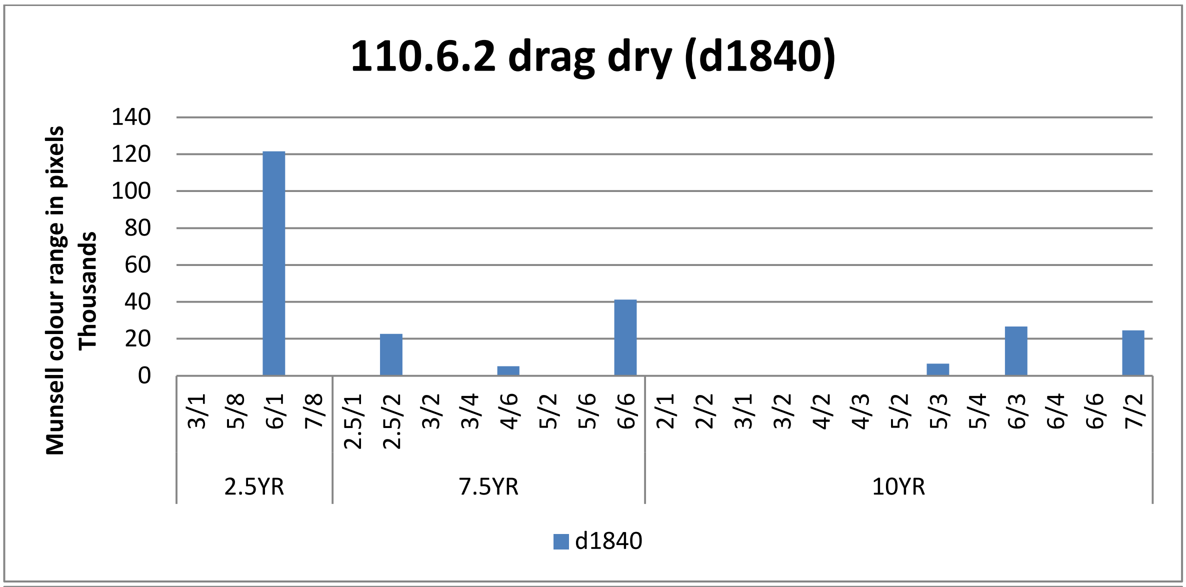

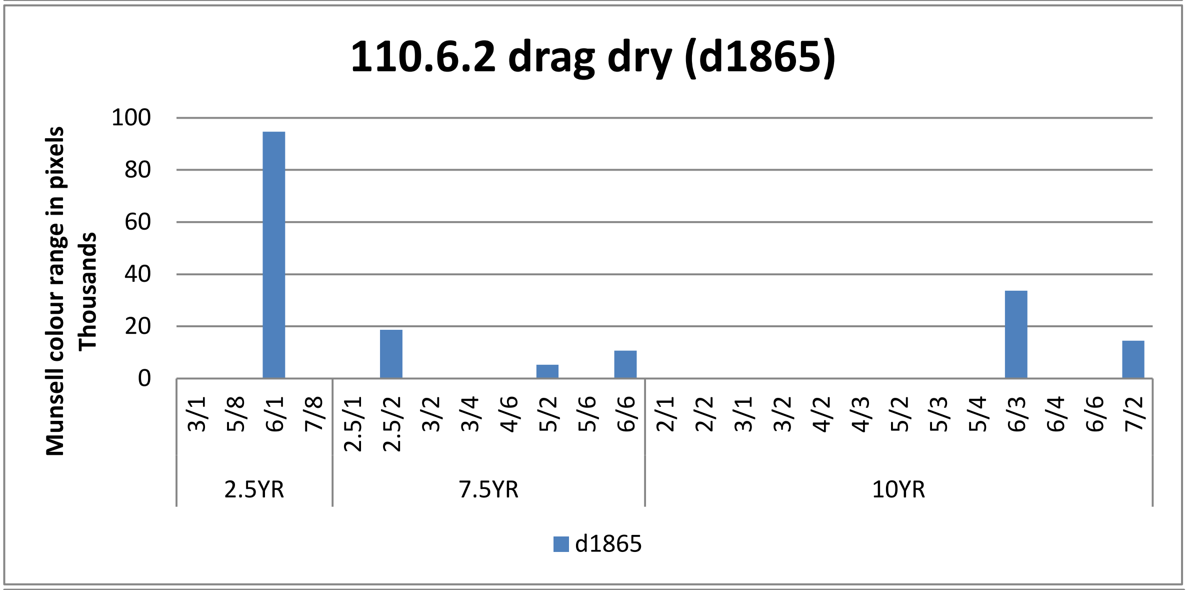

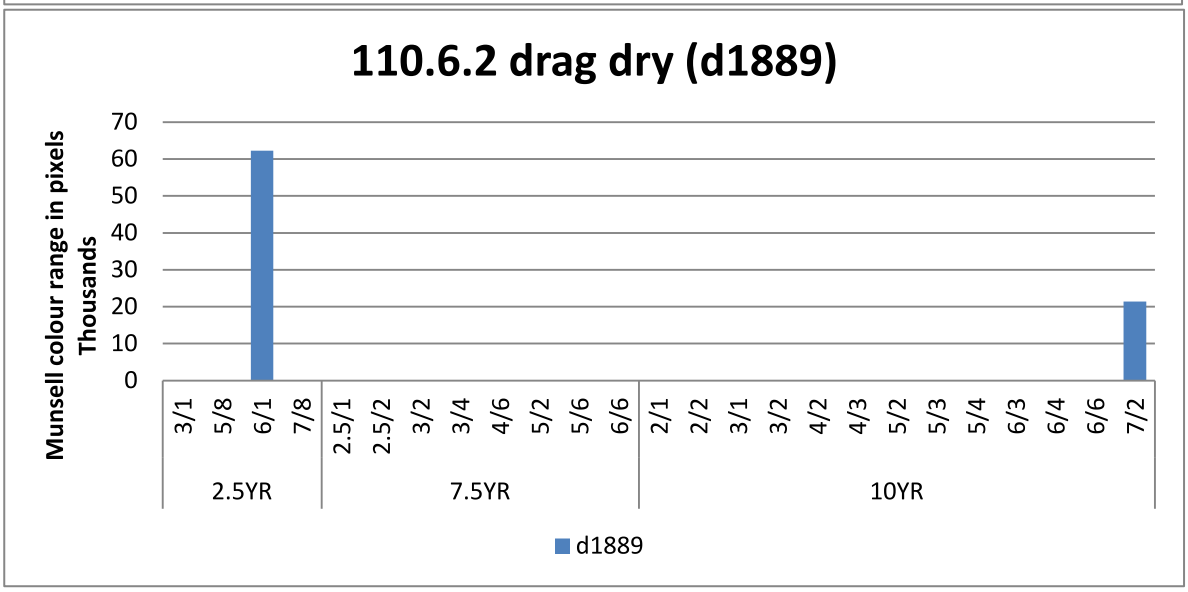

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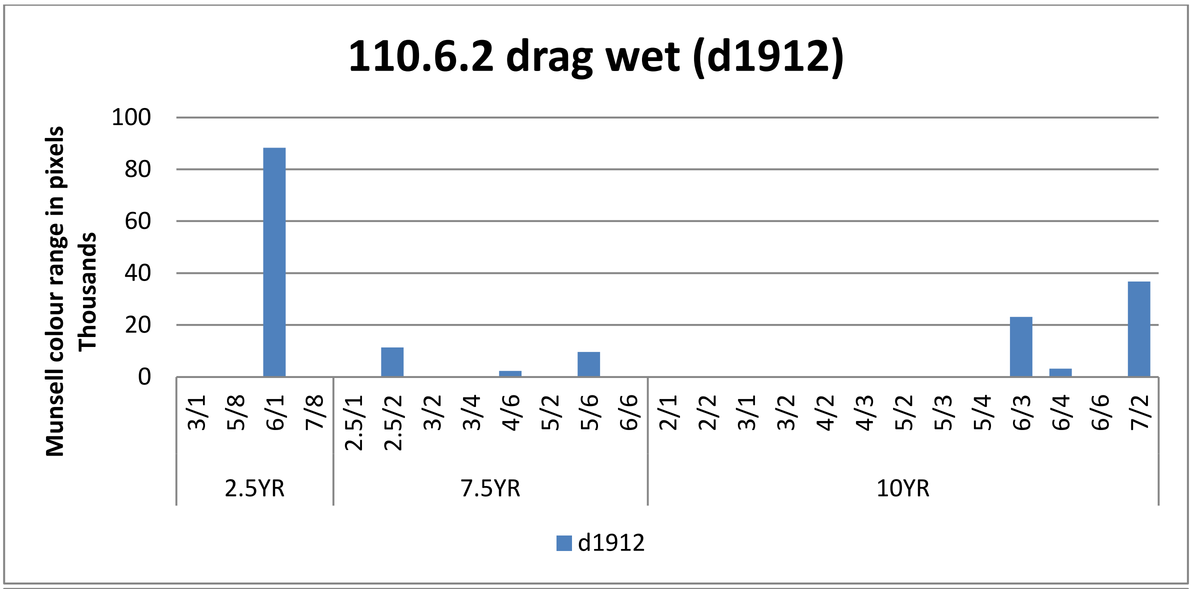

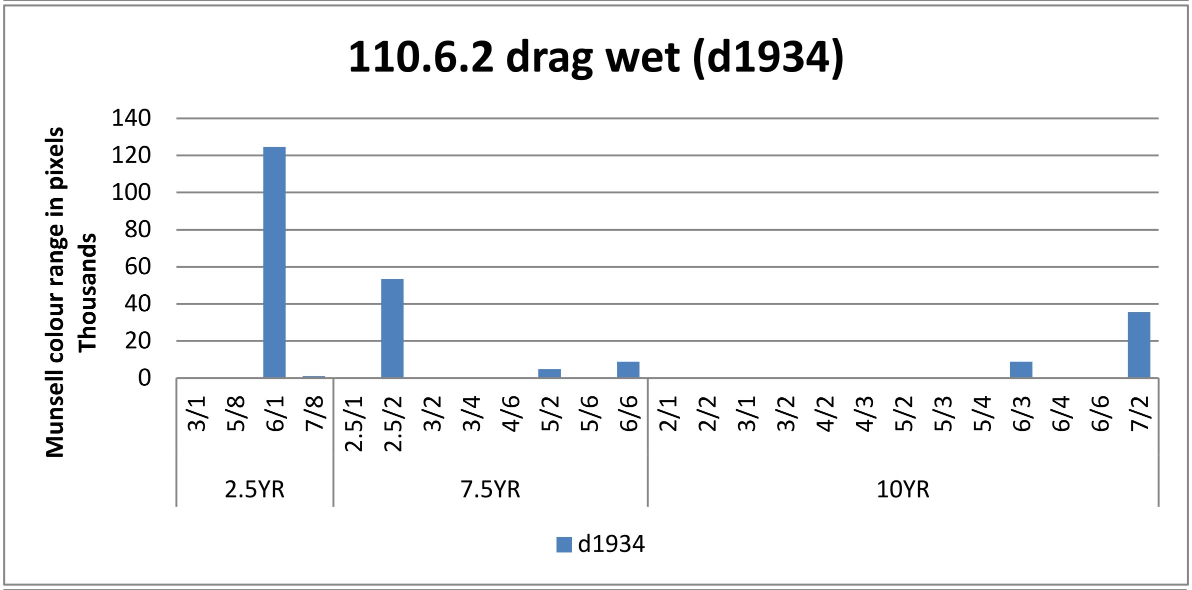

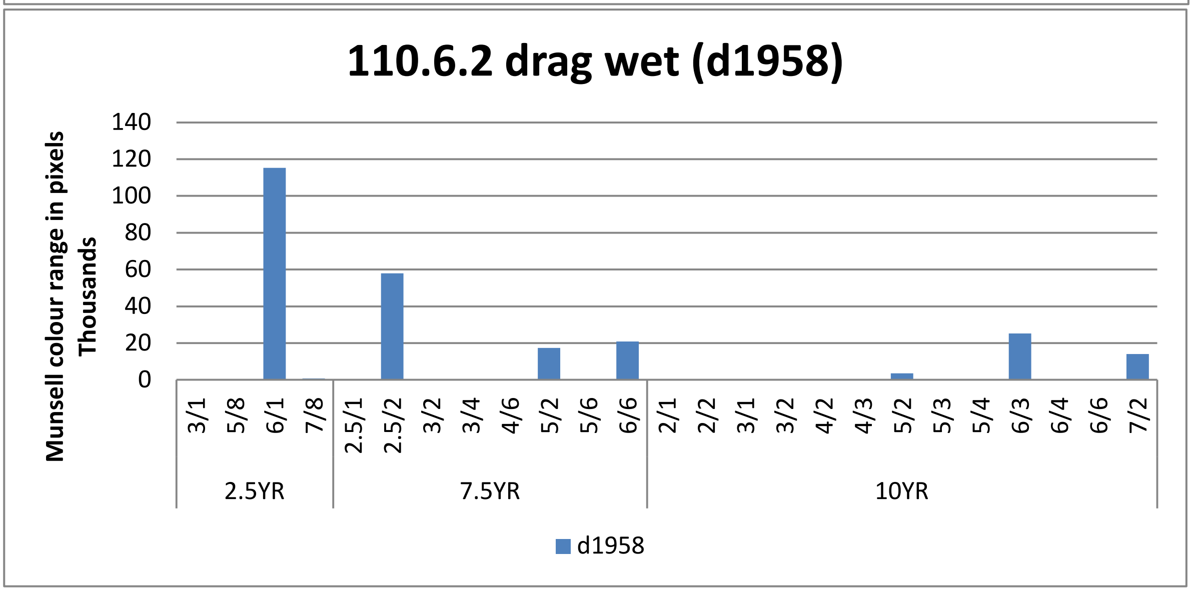

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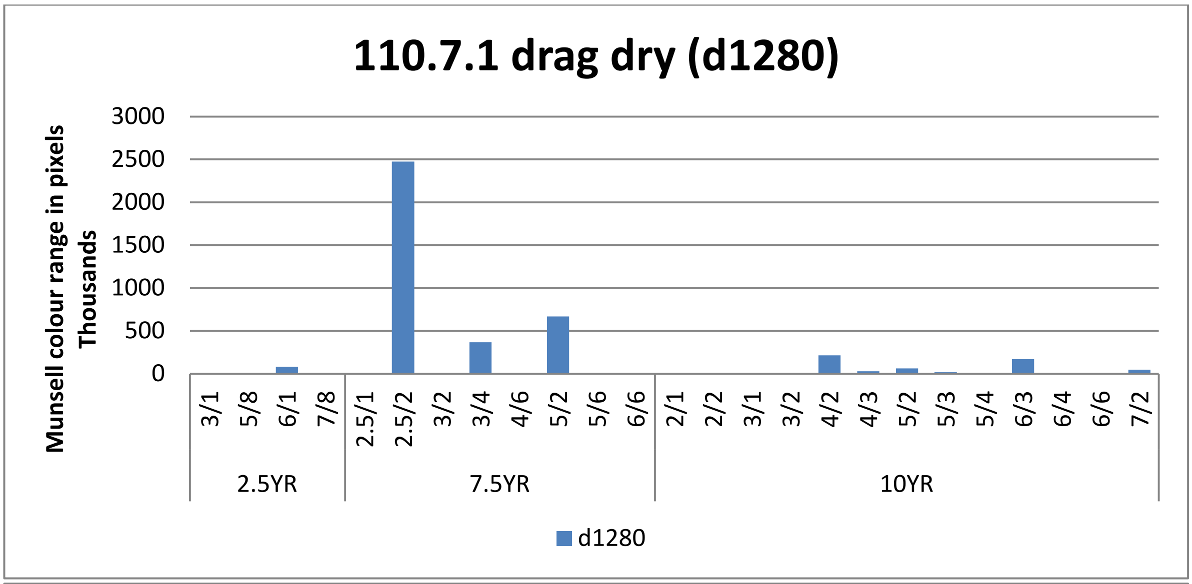

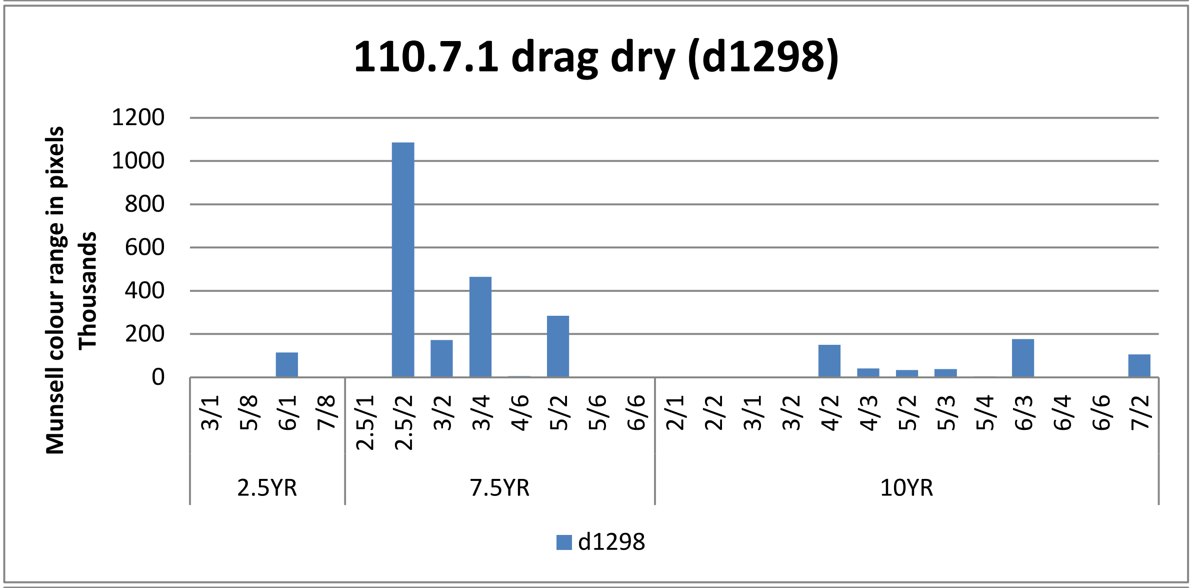

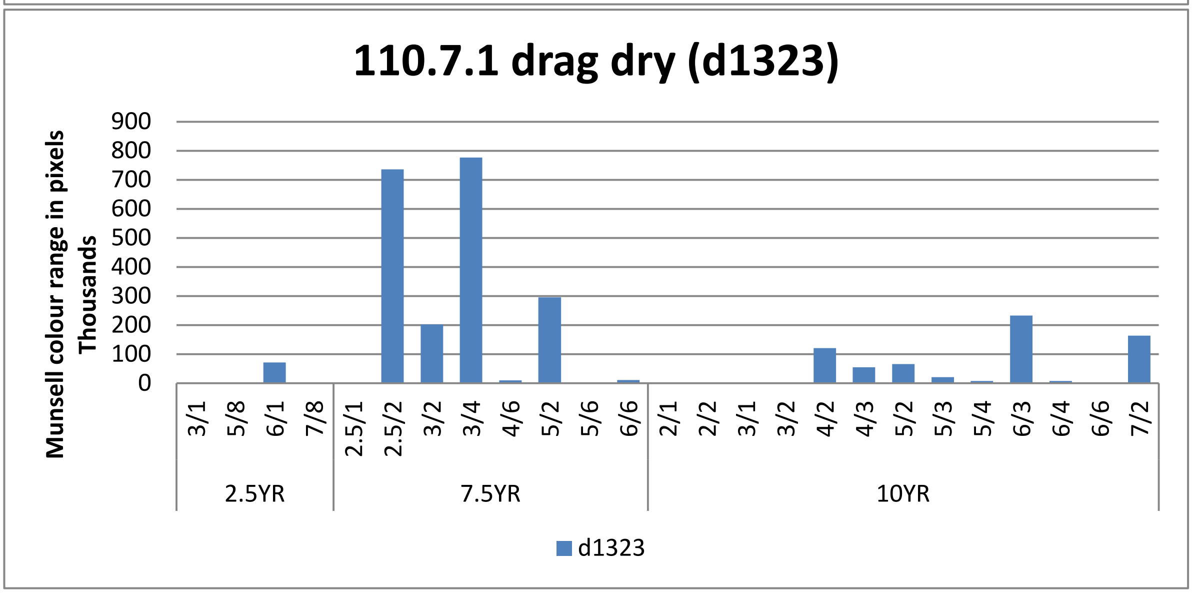

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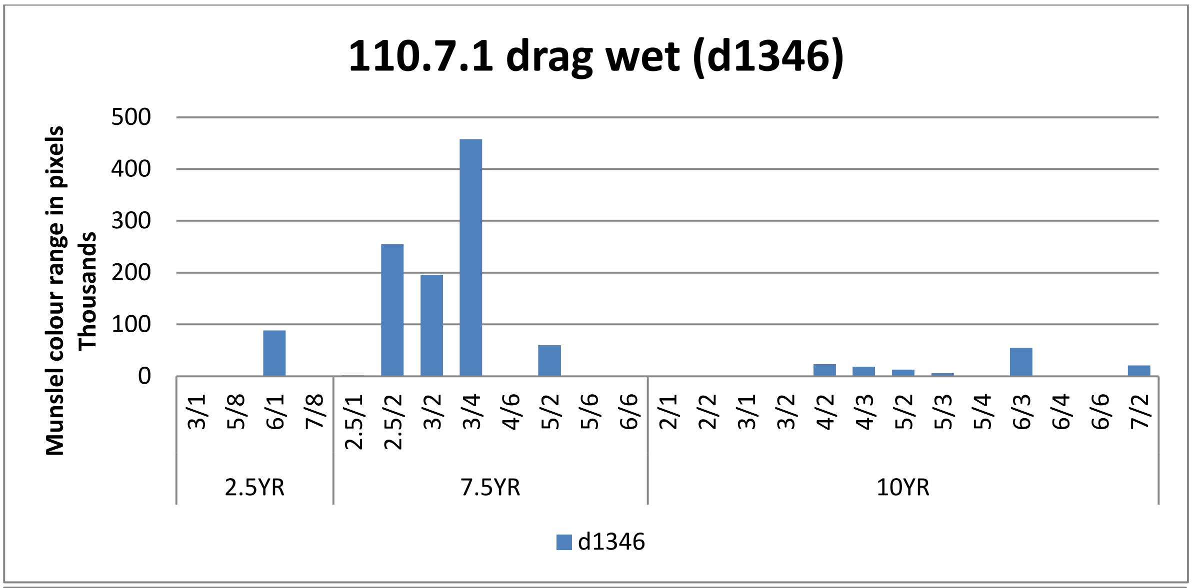

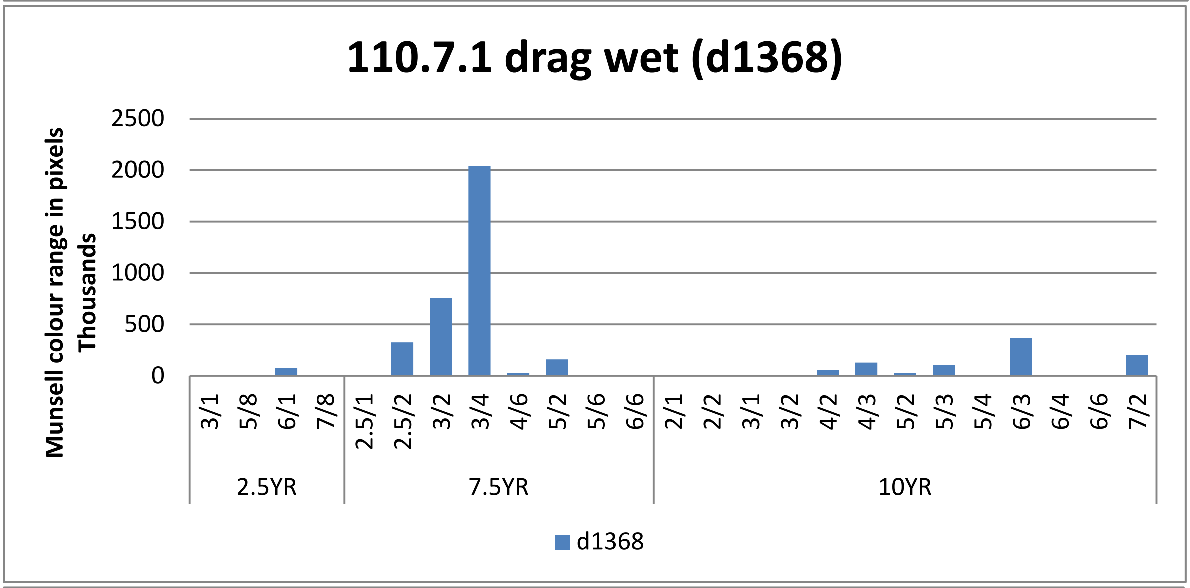

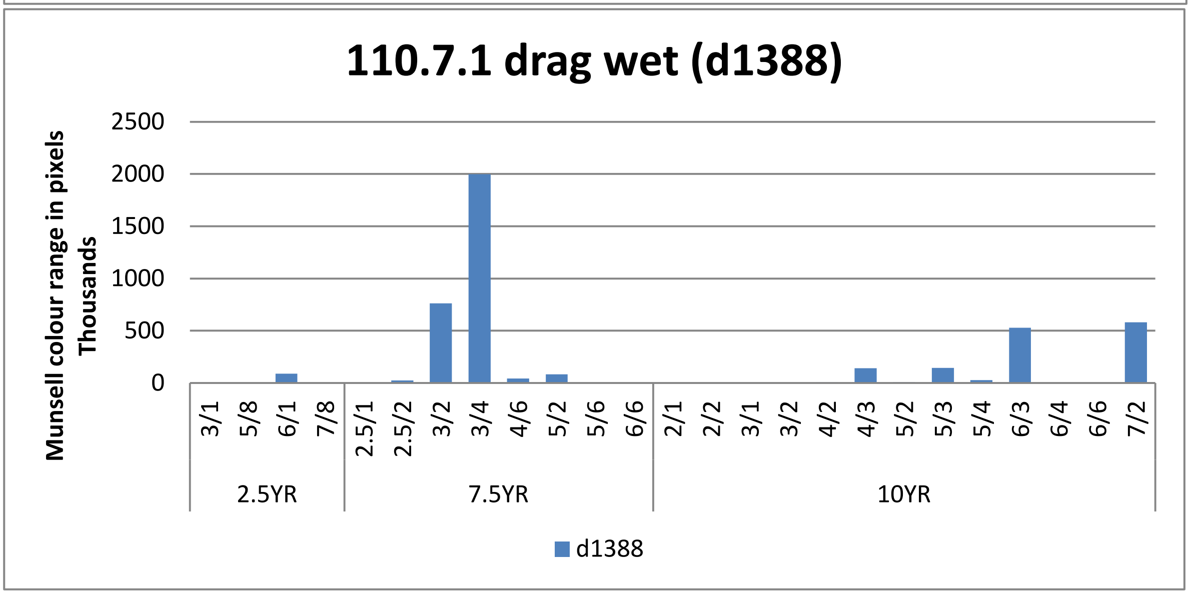

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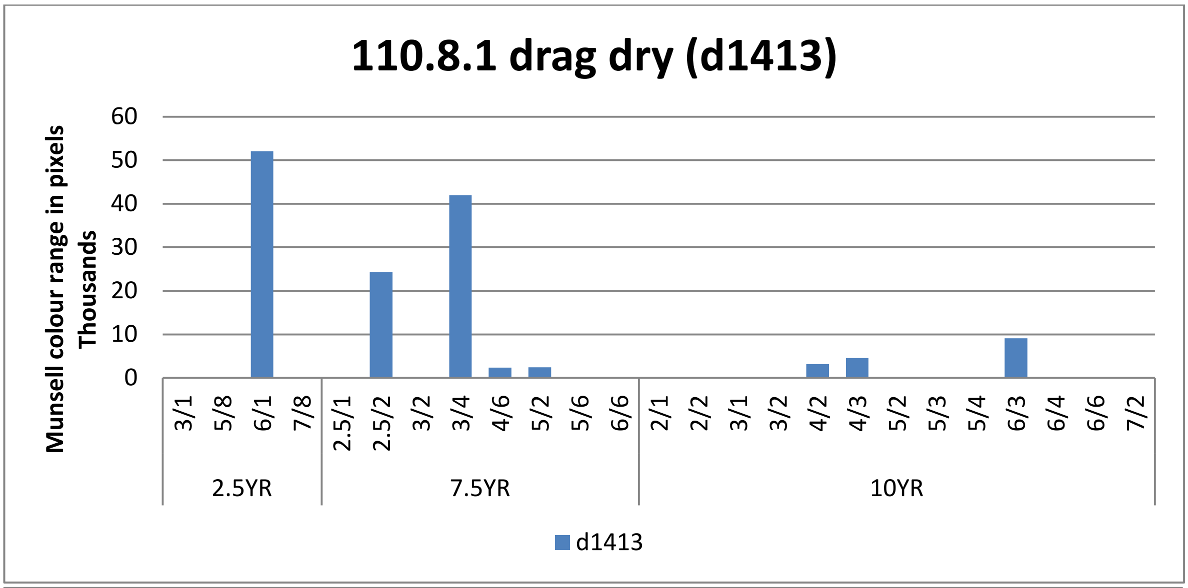

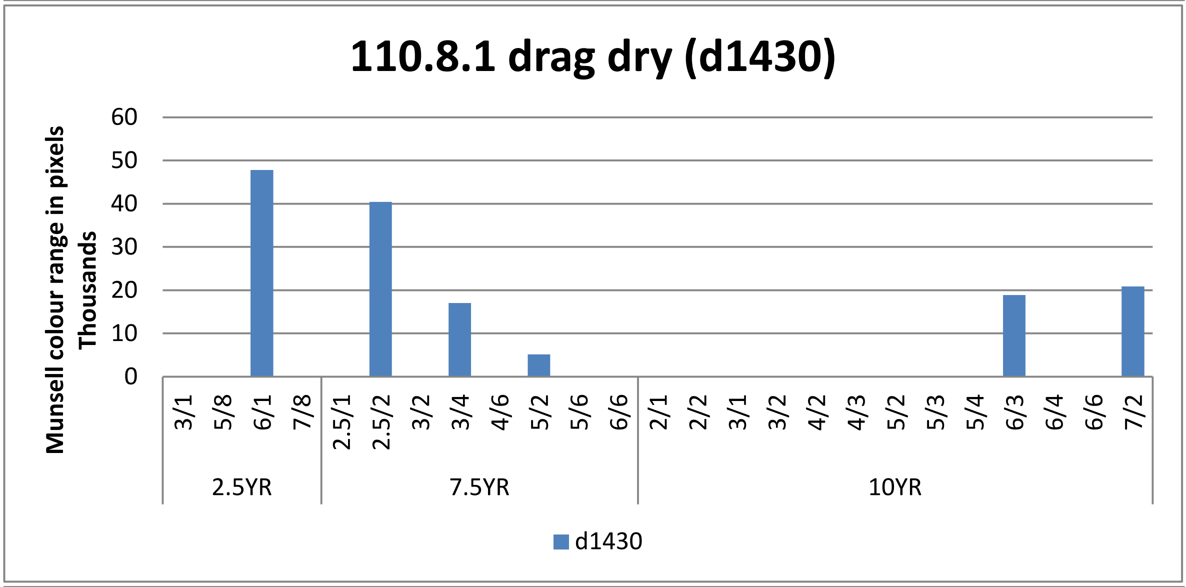

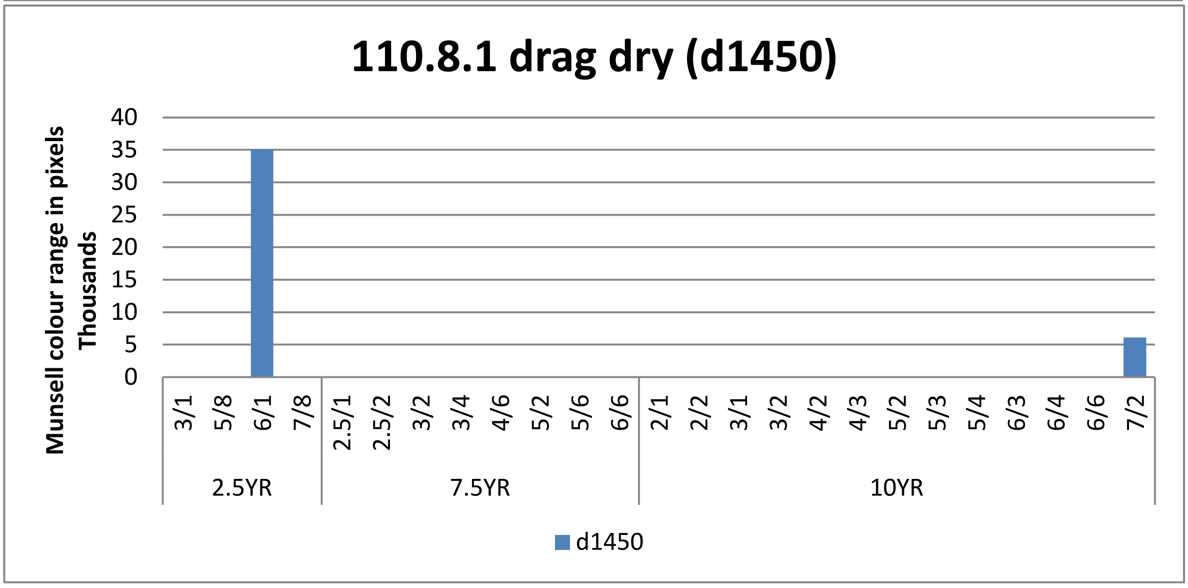

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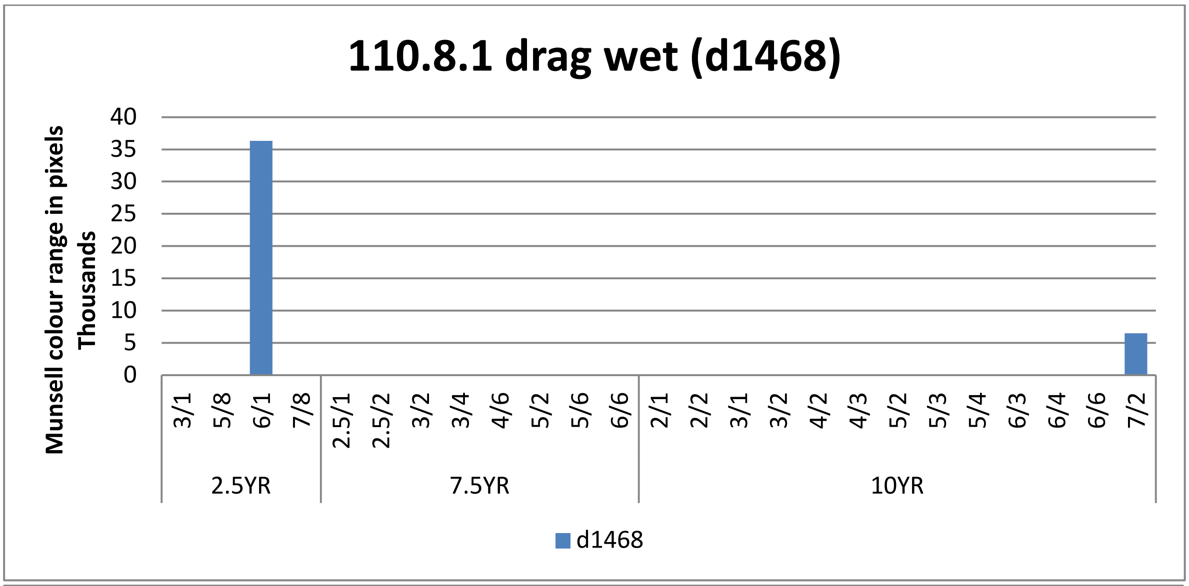

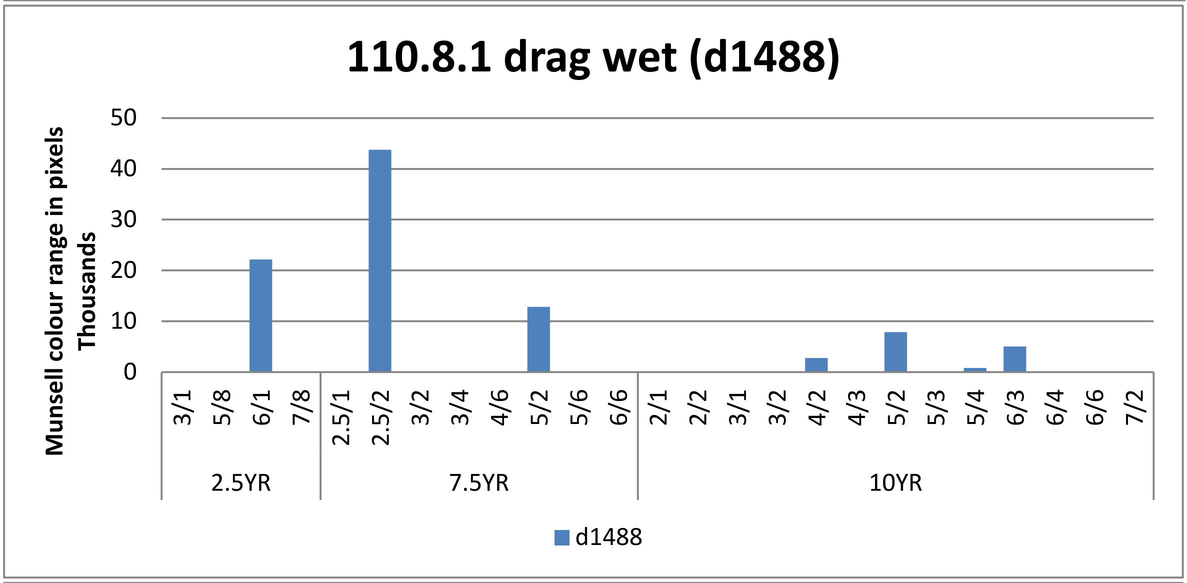

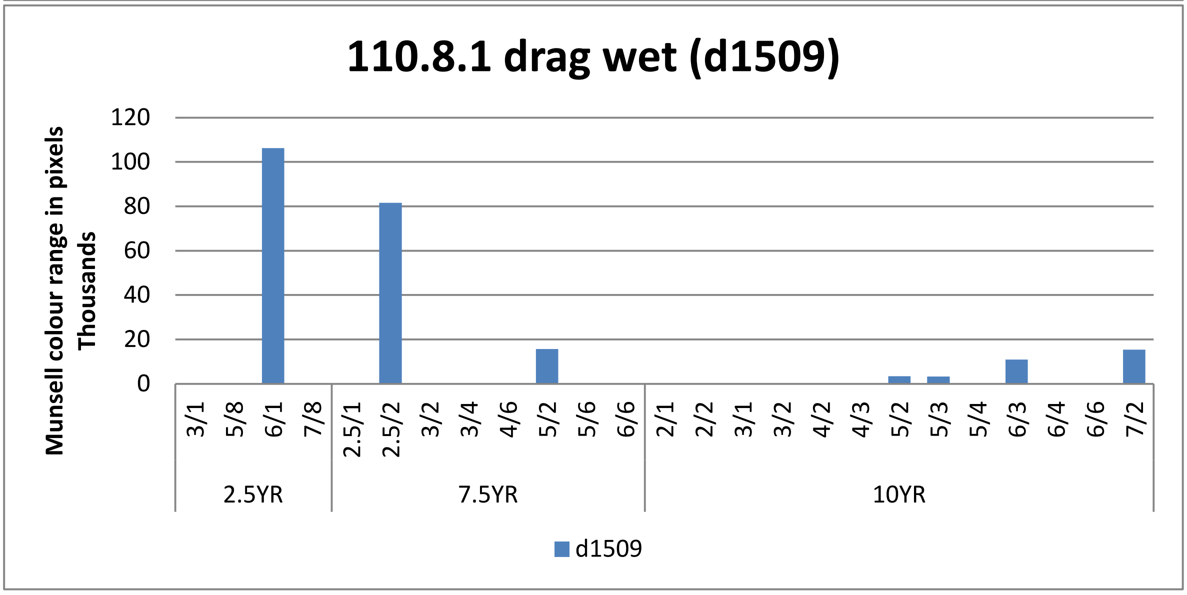

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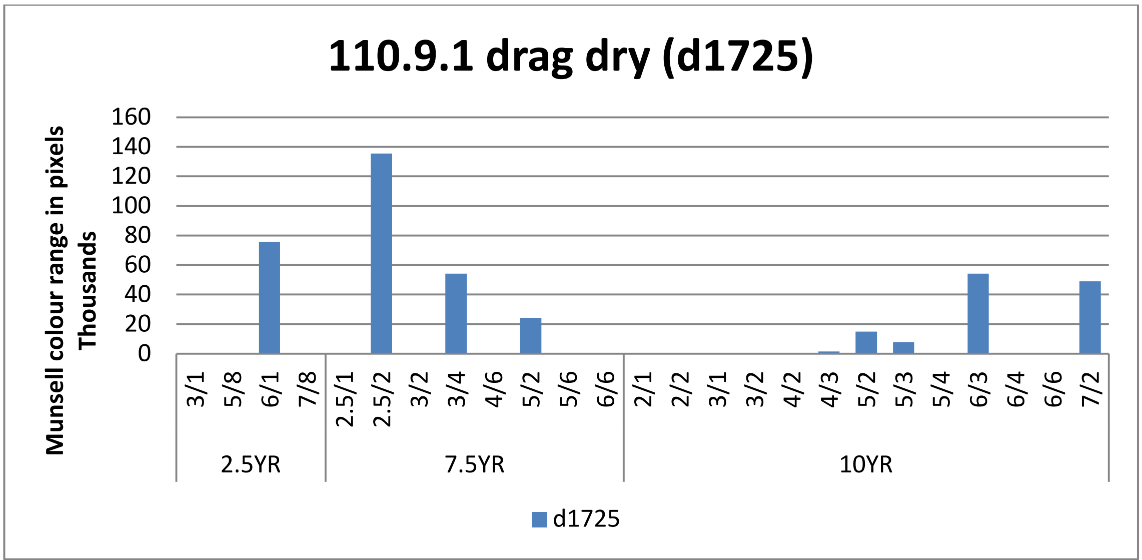

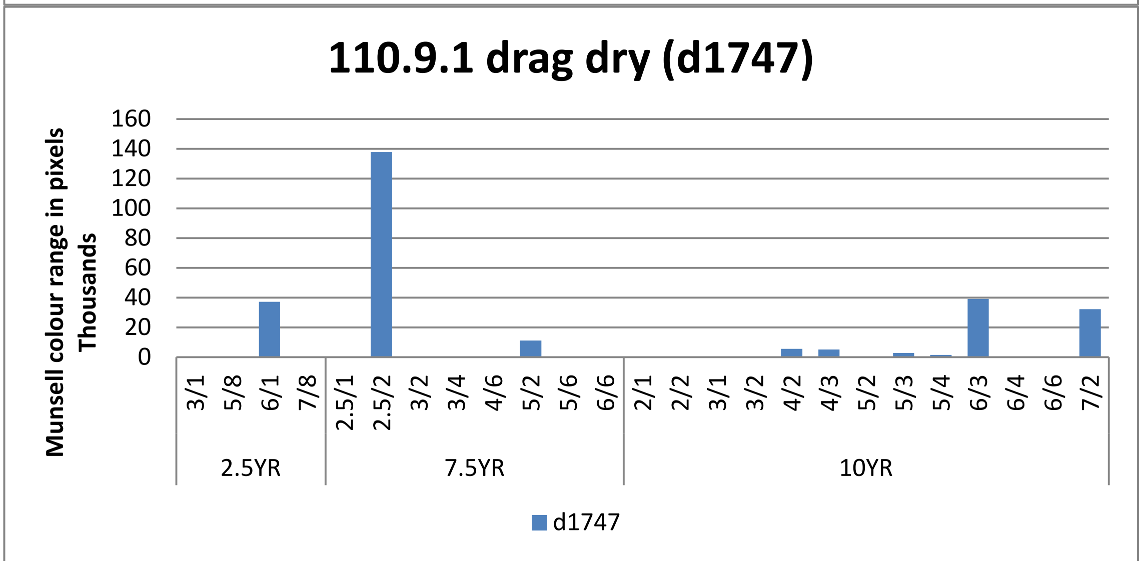

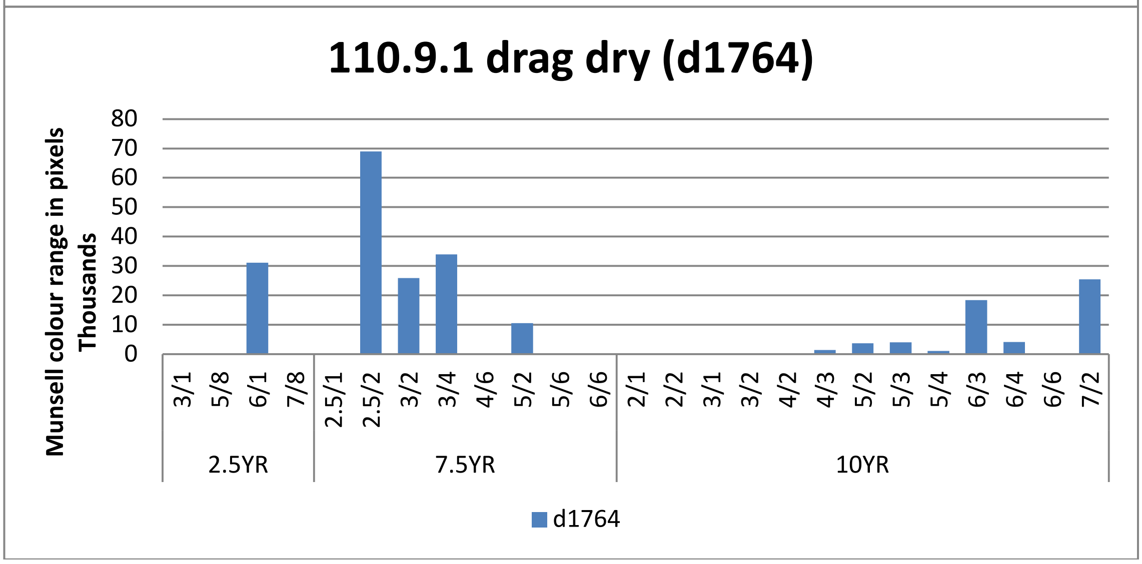

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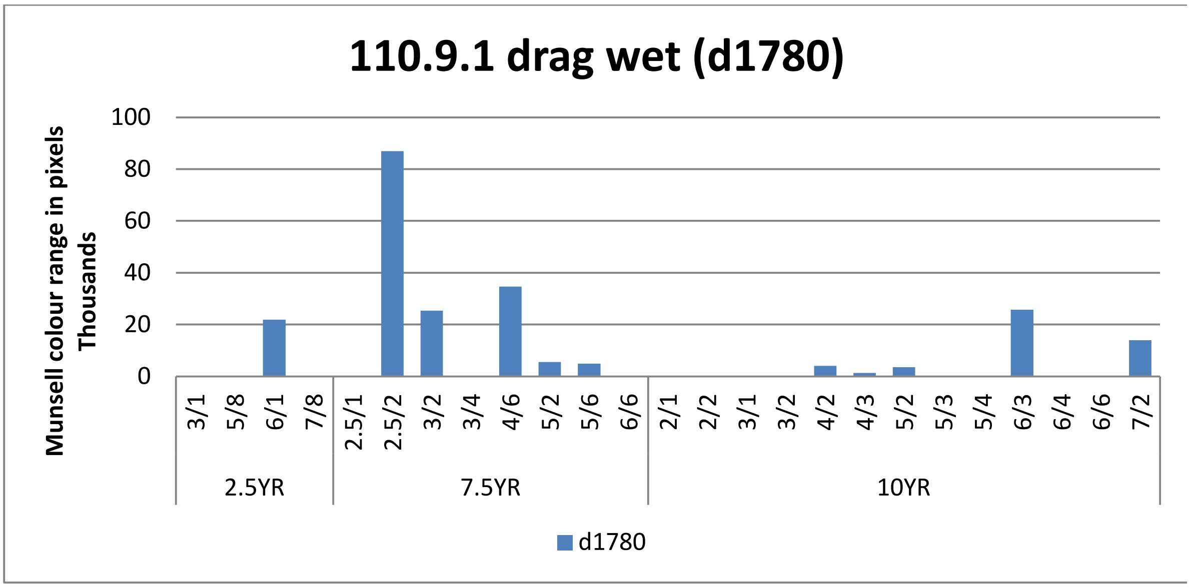

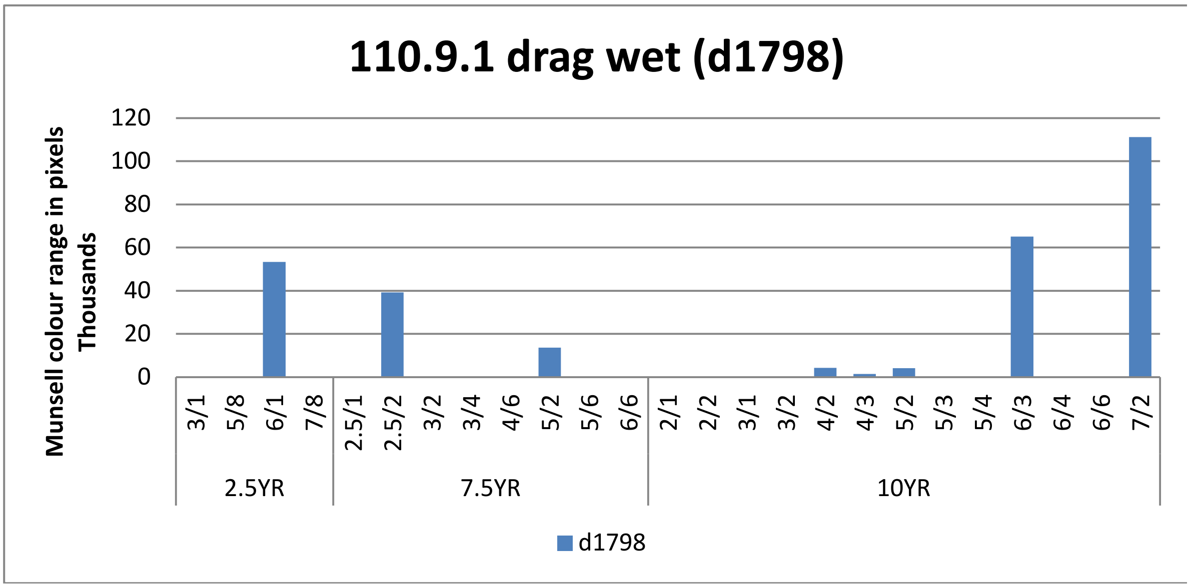

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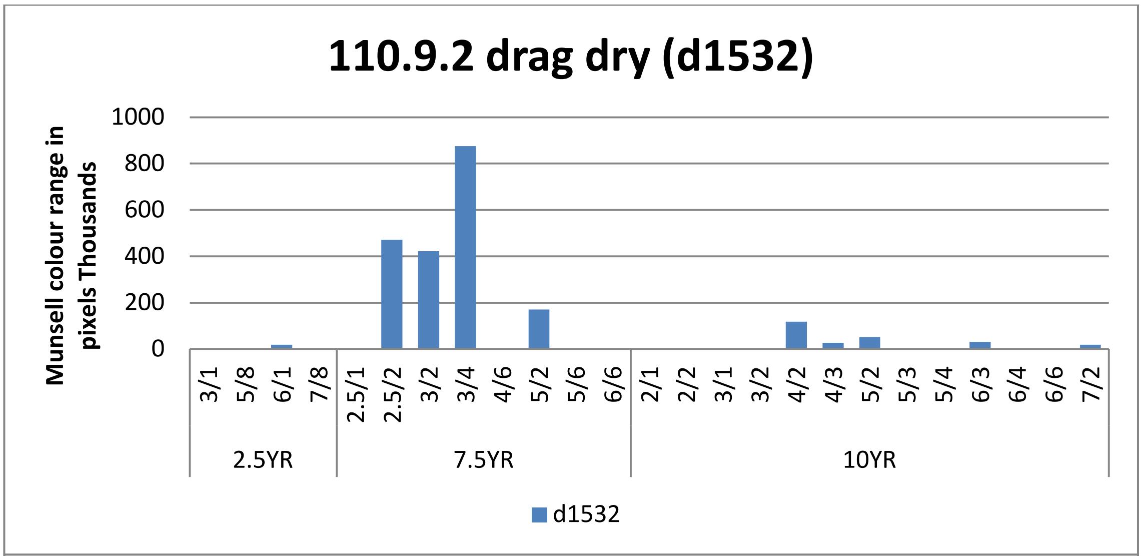

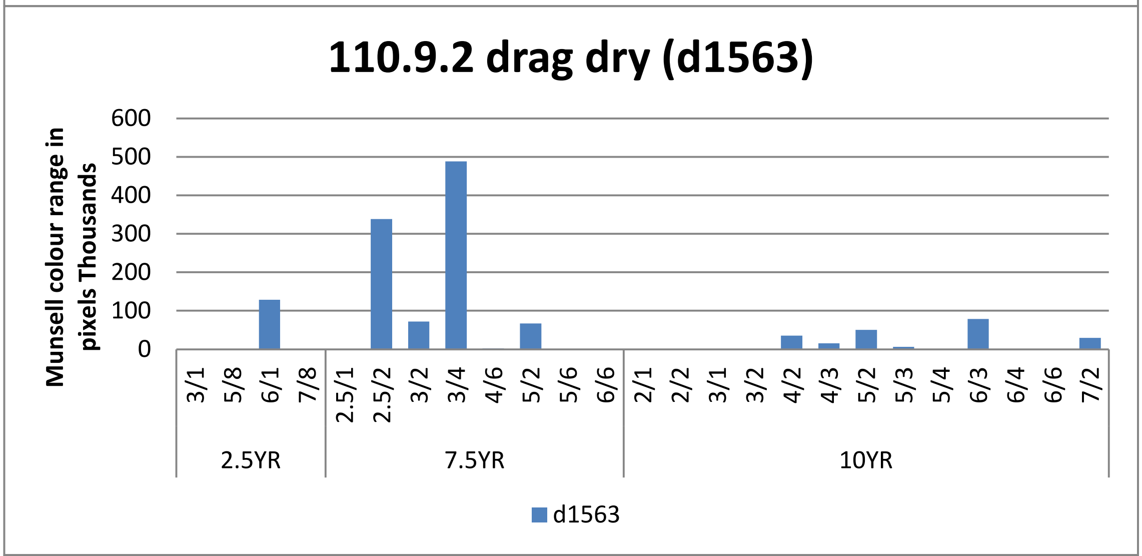

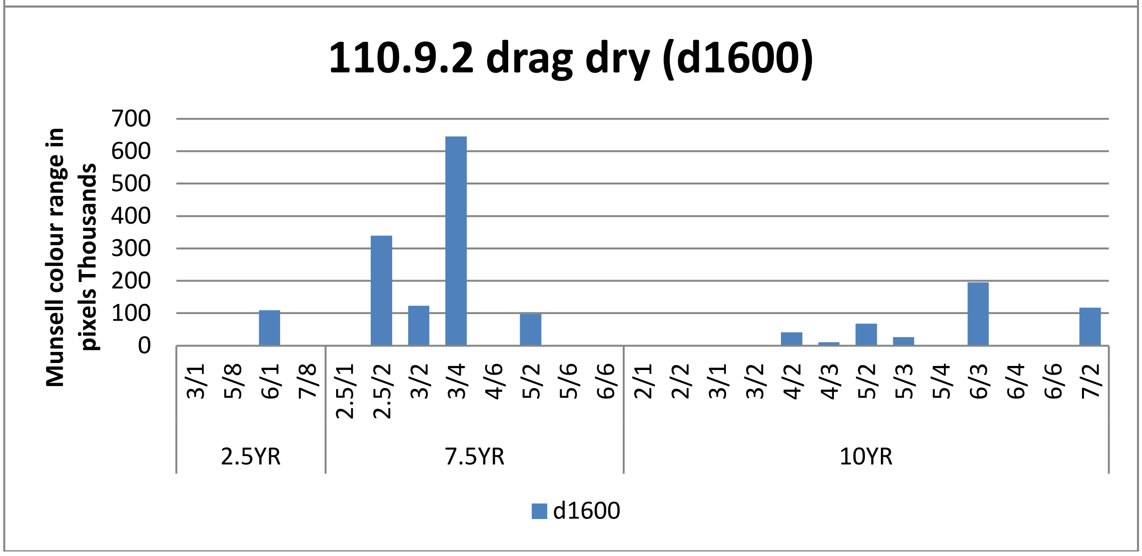

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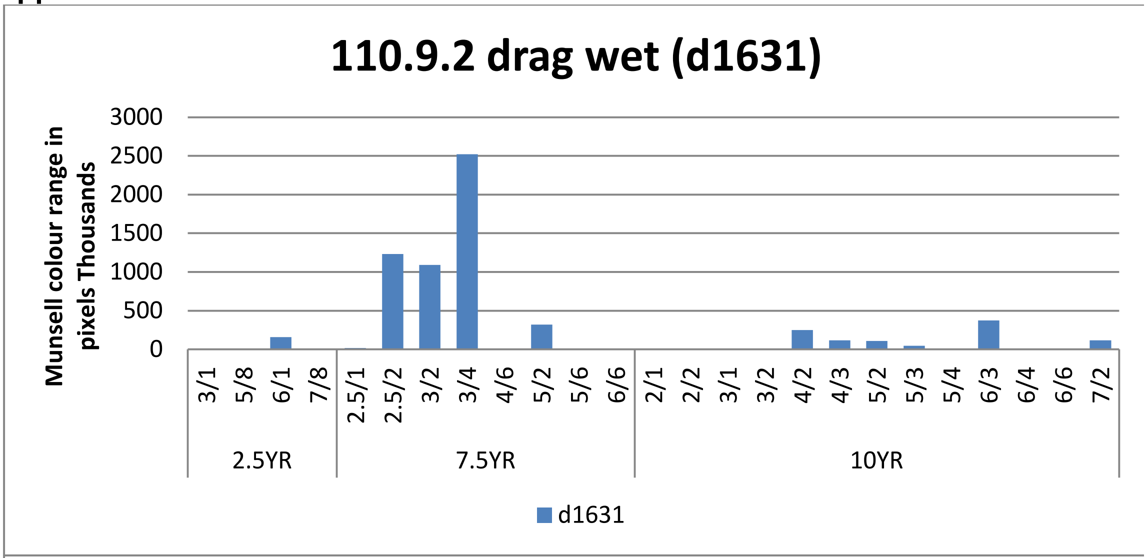
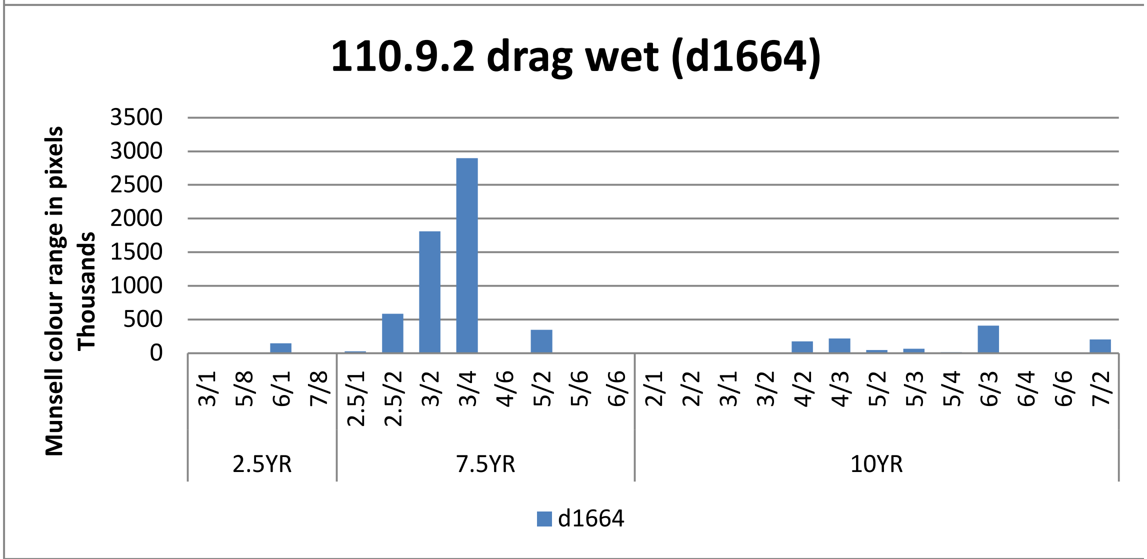
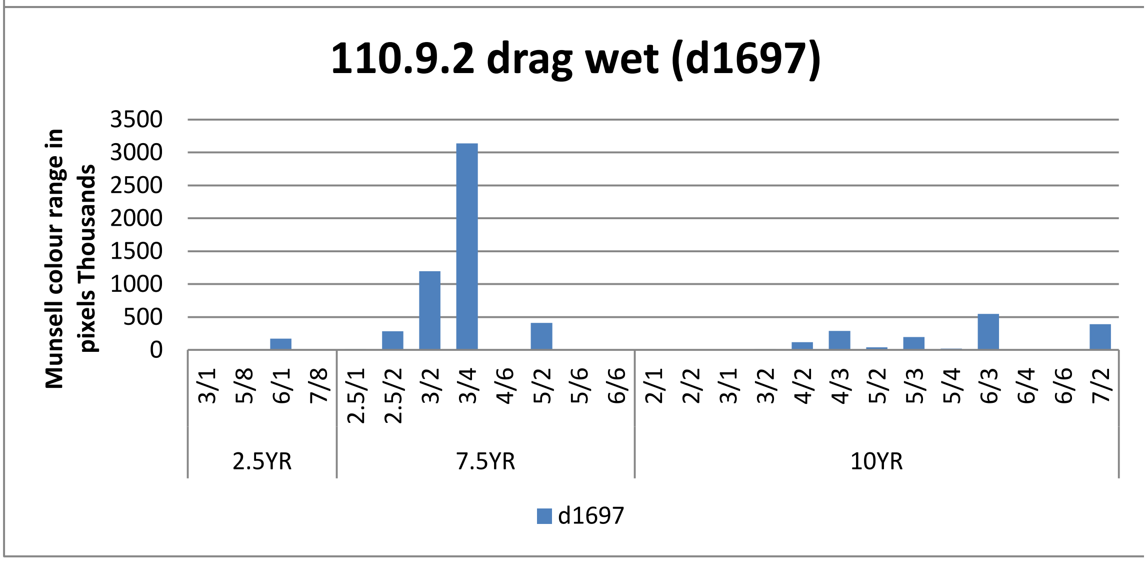
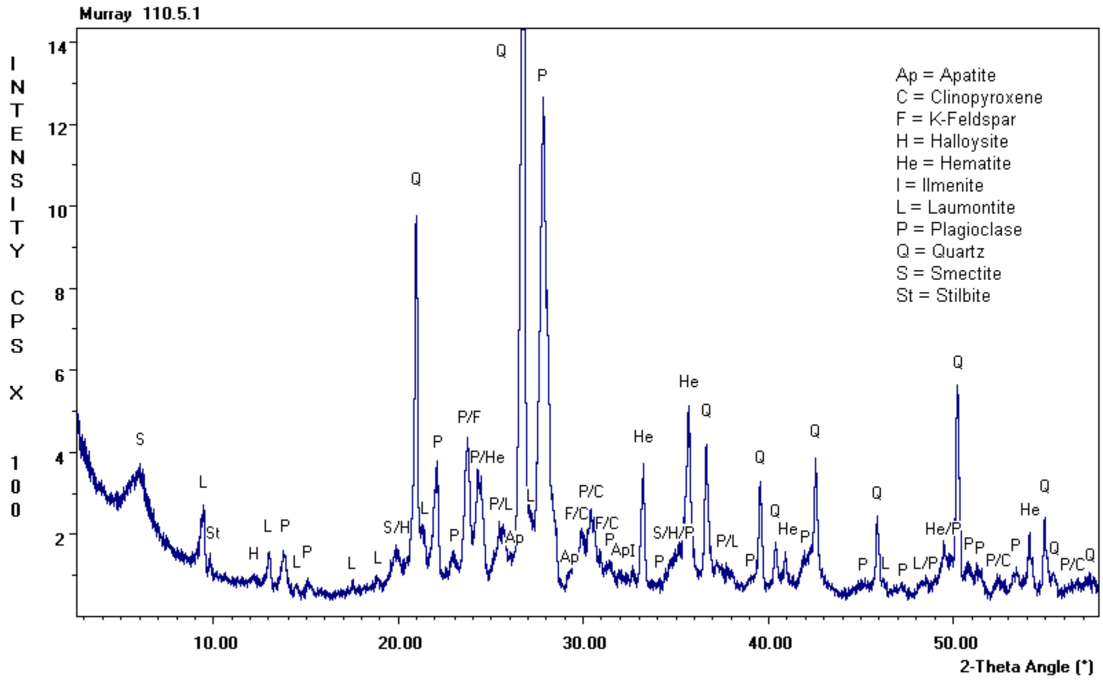




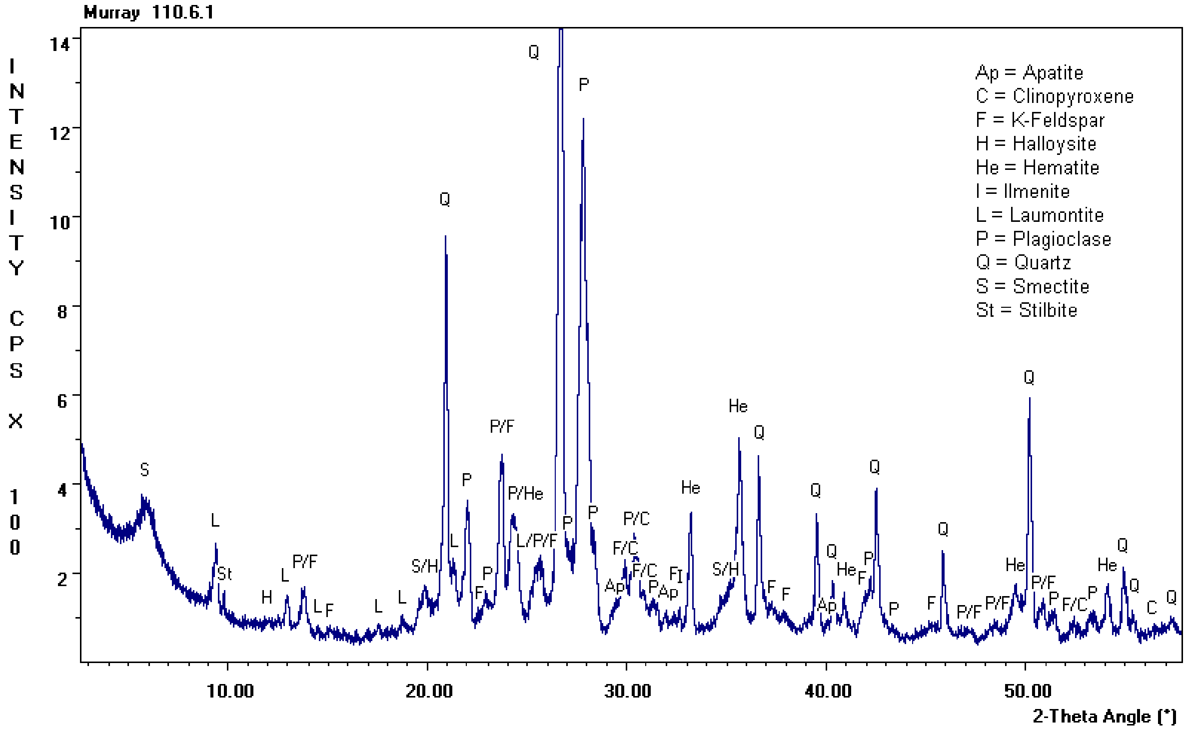


14. Appendix 4 – XRD patterns

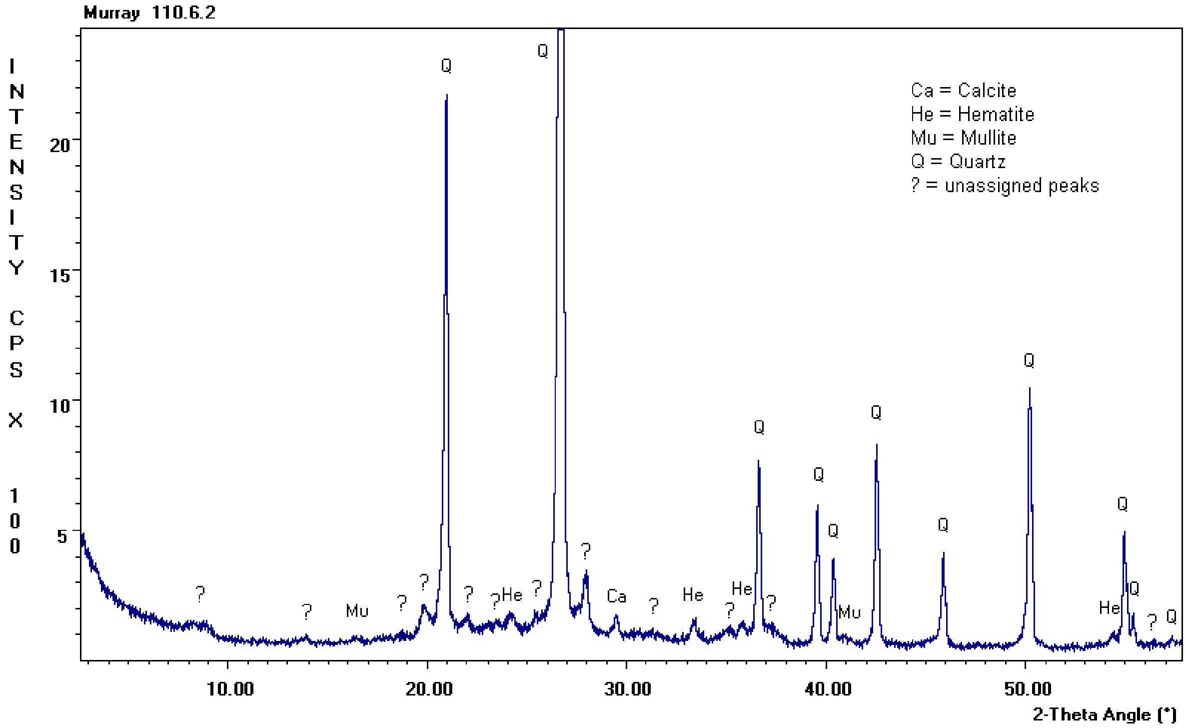
Soil no. 110.5.1	*Site 5 RTBG, Rose Garden path*	Queens Domain, Hobart	Dark brown Soil
Soil no. 110.6.1	*Site 6 RTBG, Rose Garden path near wall*	Queens Domain, Hobart	Dark brown Soil
Soil no. 110.6.2	*Site 6 RTBG, Brick fragments, near wall*	Queens Domain, Hobart	Red Soil
Soil no. 110.7.1	*Site 7 RTBG, Rose Garden bed*	Queens Domain, Hobart	Black Soil
Soil no. 110.8.1	*Site 8 RTBG, Japanese Garden*	Queens Domain, Hobart	Dark reddish gray Soil
Soil no. 110.9.2	*Site 9 RTBG, Natural soil*	Queens Domain, Hobart	Very dark brown Soil



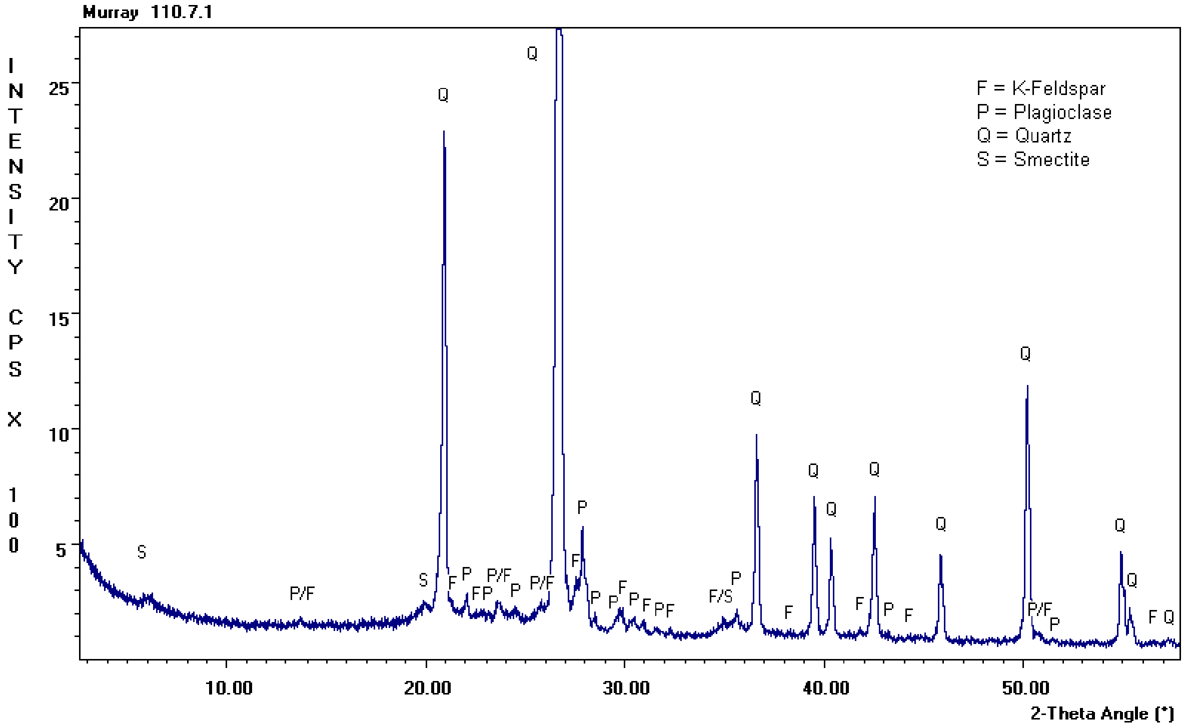
Sample no. 110.5.1: Site 5 Rose Garden path, RTBG, Queens Domain, Hobart. Dark brown Soil



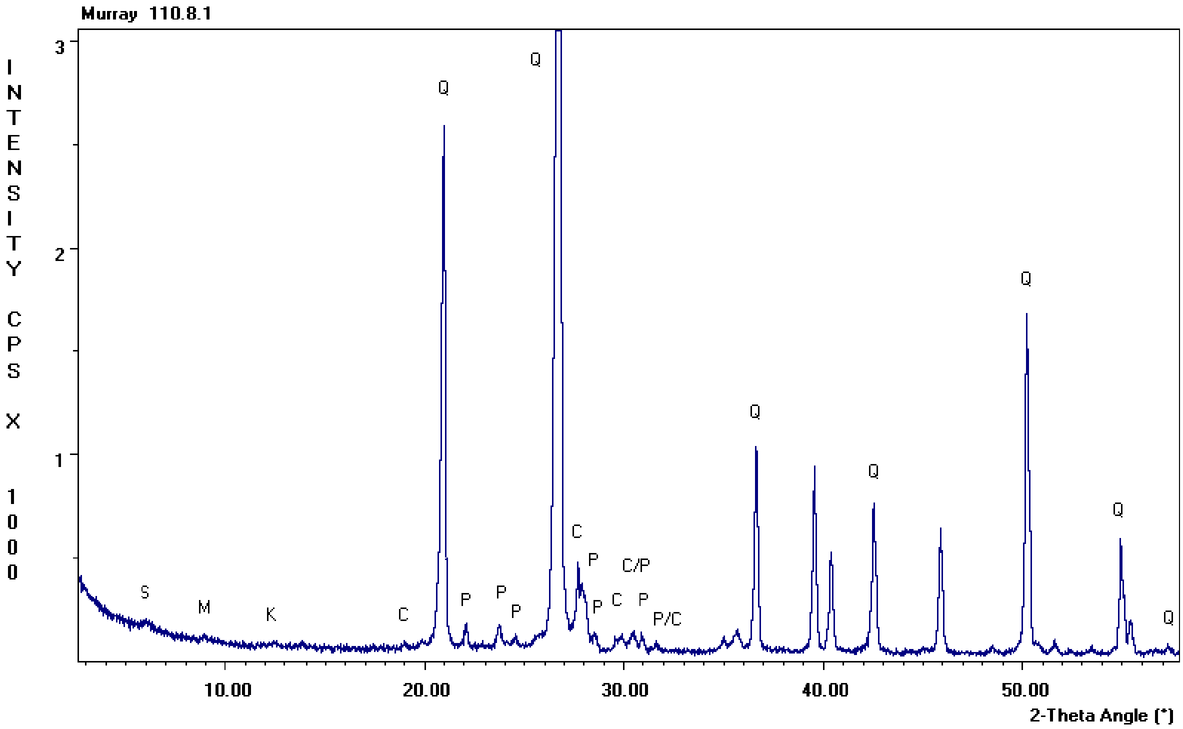
Sample no. 110.6.1: Site 6 Rose Garden path, RTBG, Queens Domain, Hobart Dark Brown soil



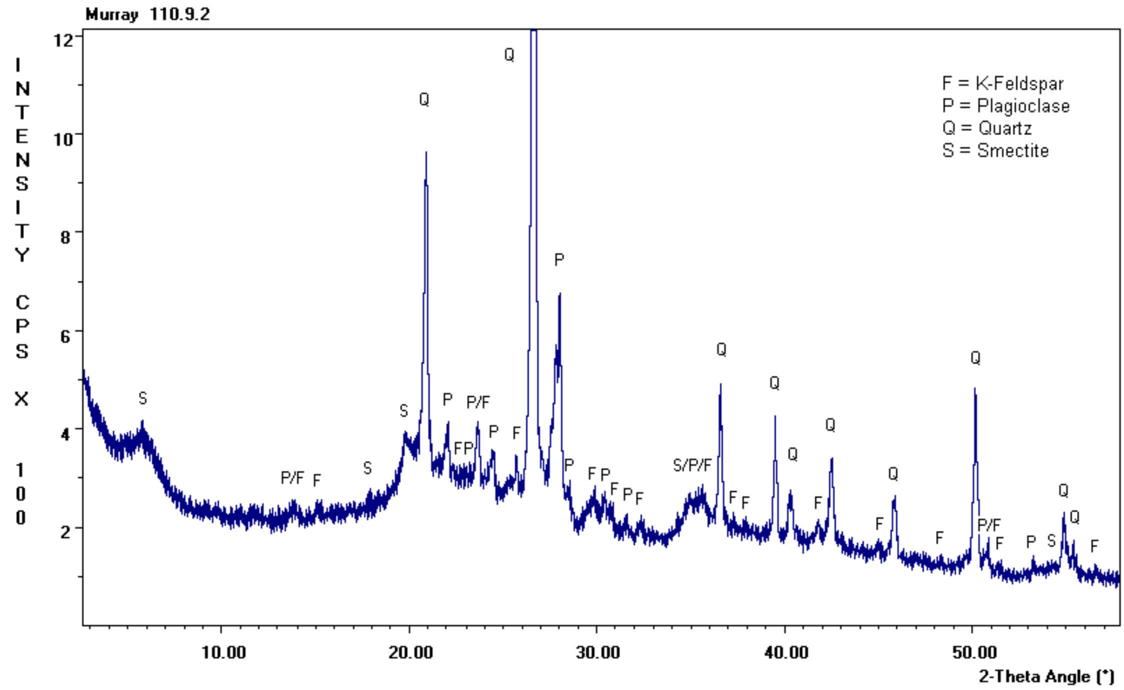
Sample no. 110.6.2 Site 6 Rose Garden path, RTBG, Queens Domain, Hobart Red Soil



Sample no. 110.7.1: Site 7 Rose Garden path, RTBG, Queens Domain, Hobart.   Black Soil



Sample no. 110.8.1: Site 8 Rose Garden path, RTBG, Queens Domain, Hobart   Dark reddish gray Soil



Sample no. 110.9.2: Site 9 Natural soil SE boundary, RTBG, Queens Domain, Hobart Very dark brown soil

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7.2 Supplementary Information: Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations

Supplementary Information

Patterns produced when soil is transferred to bras by placing and dragging actions: the application of digital photography and image processing to support visible observations

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Contents

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1. PHOTOGRAPHS OF SITES

Photographs of the following two sites in the Royal Tasmanian Botanical Gardens (RTBG), which were used in the field experiments and corresponding laboratory experiments, are shown in Figure 1-1 and Figure 1-2:

- **Site 1: Rose Garden Path with Anthropogenic soil** (Figure 1-1**)**
- **Site 2: South east boundary with "Natural soil** (Figure 1-2).

Figure 1-1 Photograph of the Rose Garden path in the Royal Tasmanian Botanical Gardens Lower Domain Rd, Hobart, Tasmania, Australia.

Figure 1-2 Photograph of the natural soil under deciduous trees near south eastern boundary of the Royal Tasmanian Botanical Gardens, Lower Domain Rd, Hobart, Tasmania, Australia.

2. FIELD AND LABORATORY METHODS

2.1 Total carbon and sulfur

The carbon and sulfur content of the soil samples were determined using Nondispersive infrared (NDIR) analysis.

The carbon and sulfur contents of the soil samples were determined by Nondispersive infrared (NDIR) analysis using a Bruker G4 Icarus analyser, in the MRT laboratories, Rosny Park. The following standards were run during analyses to check calibration: AR4005 (C=1.42%, S=1.41%), AR4013 (C=2.93%, S=0.020%), AR4014 (C=5.87%, S=0.029%), AR4007 (C=7.27%, S=3.26%) and AR4024 (C=11.72%, S=0.418%).

2.2 Mineralogical analyses by x-ray diffraction

Analysis of the XRD patterns were performed using CSIRO XRD software: "VisualXRD", "PW1710 for Windows" and "XPLOT for Windows". Mineralogical phase identification were made by manually comparing the measured XRD patterns with a series of similarly-prepared standards of the more common minerals to enable some semi-quantitative analysis. Quartz, if present, is used as an internal standard. If quartz is not present, it is routinely added to the sample for a supplementary scan. The semi-quantitative results are calculated using single-peak calibration factors derived from scans of known mixtures of minerals. This follows the methods of Maniar and Cooke (1987) and Chung (1974); which are variants of the internal standard and matrix flushing method of Klug and Alexander (1954).

2.3 Sports bra

The unpadded, underwire, sports bra used in all these experiment has three hook-and-eye back fasteners, underwires rising high between the cleavage, unpadded cups, and sliding shoulder-straps with metal buckles. The bra's fabric is nylon-elastane. A DD-cup size provided a large fabric area for experiments and the white fabric made it easier to locate and identify trace soil transferred. To smoothly stretch the bra-cup fabric with a replication of a human breast, the bra was padded with a sock filled with rice (protected by a plastic cliplock bag with the smooth surface facing out and all corners taped securely to the back of the bag).

2.4 Soil transference experiments to test the transfer method of placing or dragging a human rescue dummy dressed in clothing (bra) across soil surfaces

Experimental design

A life-like rescue dummy from LifeTec came dressed in waterproof overalls and gumboots. A waterproof nylon-reinforced PVC bag was then duct-taped over its head and two 'sacrificial' plastic clip-lock bags duct-taped over this and secured to the collar of the overalls. Two plastic clip-lock bags were also duct-taped to each hand. The entire hand was then duct-taped over and attached to the cuffs of the overalls. A clean bra was firmly fitted and removable ‘breast implants’ positioned deep within each cup. Each implant consisted of a sock filled with 700g of rice. This was knotted, excess sock material removed and then firmly enclosed in a plastic bread bag. The end of the plastic bag was tied, cut and smoothly secured with duct-tape. The implant was always fitted with the knotted side pressed against the dummy. Fully attired, the rescue dummy weighed in at 55kg with ‘breast implants’.

To identify the soil transfer patterns that occur when a body wearing clothing (a bra) is placed on a soil surface, the dummy wearing a clean bra is placed on its back on the target soil for 2 minutes. The placing STE is then repeated with the dummy turned onto its front for a further 2 minutes, whilst detailed photos are taken of the STE just completed on the back of the bra. Then once the second STE is completed, the dummy is gently placed on its back on a clean plastic groundsheet; whilst extensive photos are taken of the front of the bra. This test was run three times each on the front and back of the bra; first using dry, then wet soil.

In order to identify the soil transfer patterns that occur when a body wearing clothing is dragged across a soil surface, the rescue dummy wearing a clean bra was first placed on its back for a 5 second count. During this time, the assistant dragging the dummy takes a firm grip on its legs. The dummy is then dragged for 3m. During a final 5 second count, two attendants take one dummy arm each and then lift the dummy’s torso in unison. It is vital to raise the bra cleanly from the soil without smudging the soil transference patterns. The dummy is then placed on its front on a clean plastic groundsheet whilst detailed photos are taken of soil transference patterns on the back of the bra.

The dragging STE is then repeated with the dummy dragged on its front, before being gently placed on its back on the clean groundsheet to photograph these new soil transference patterns. This test is run three times each on the front and back of the bra; first using dry, then wet soil.

The same assistant was used for all 24 dragging STEs to keep results consistent. At 174cm tall and weighing 67kg, the 66 year old assistant dragged the 55kg dummy at a consistent speed for a total of 36 metres. He also helped a second assistant to place and manoeuvre the rescue dummy in another 24 placing STEs.

The results of all STEs were photographed in situ with a Sony Cyber-shot DSC-W530 14.1 megapixel camera.

Low-powered binocular microscopy using a WILD Heerbrug M5-53707 microscope was undertaken on bulk soil samples taken from the RTBG and on 48 trace soil samples from 48 bras used in the STEs. Digital photomicrographs were taken using the Leica DFC-425 and the Leica Application Suite, Version 3.6.0.

In order to hold the fabric flat whilst it is photomicrographed back in the laboratory, the bra was secured to a flat 2kg weight by a rubber band (Figure 1-1). This process alone dislodged an unknown amount of transferred soil particles from the surface of the fabric; as did removing the bra from the rescue dummy and transporting it to the laboratory by motor vehicle.

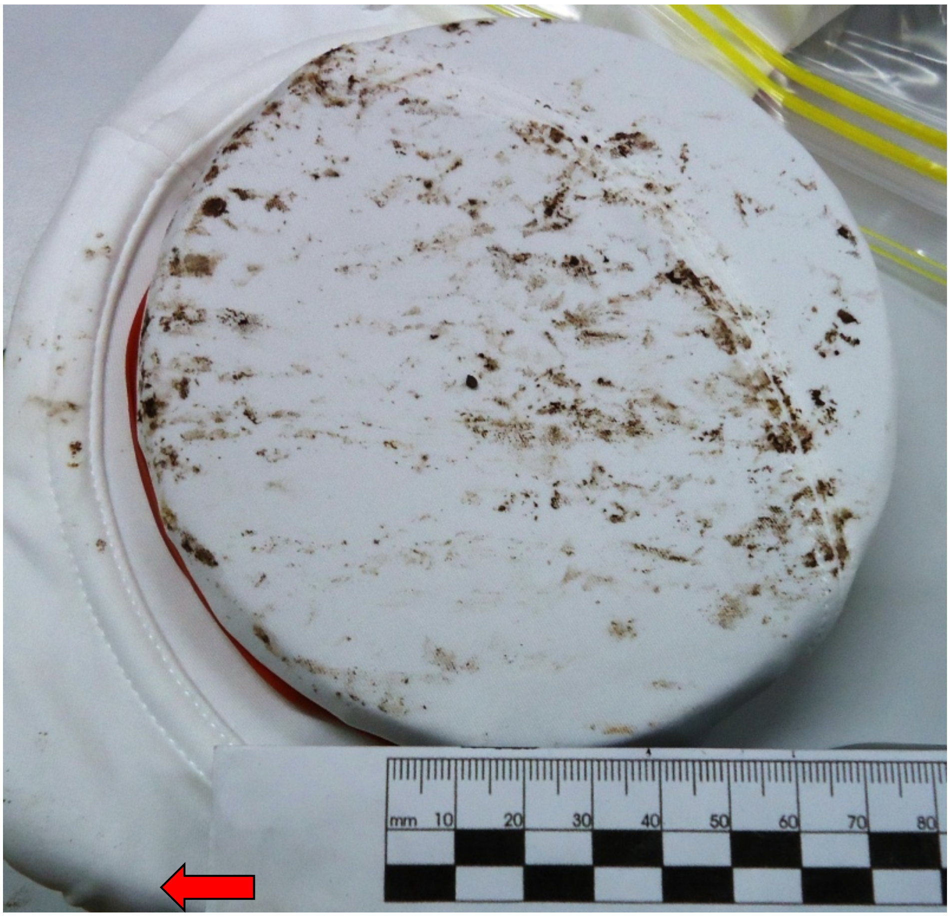


Figure 2-1 Before being photomicrographed back in the laboratory, the bra is secured to a flat 2kg weight by a rubber band (Direction of movement = right to left).

In preparation for the wet runs, the soil surface at each location was sprayed with a hose with a spray attachment until the soil colour changed evenly and water beaded. Between each run, at the natural soil site covered with dry leaves, the soil surface would be gently levelled by hand without compacting the soil surface.

3. MINERALOGY, CARBON AND SULFUR ANALYSES

3.1 Mineralogy

In order to ascertain how soil's unique mineralogy, carbon and sulfur content influenced subsequent soil transfer patterns seen across the two soil types tested, mineralogy, carbon and sulphur analyses were undertaken (Bottrill and Woolley 2014).

The semi-quantitative determination of minerals in the whole soil by X-ray diffraction (XRD) is presented in Table 2-1. XRD analysis of soil samples from the Royal Tasmanian Botanical Gardens revealed quartz as the major mineral in these soils. Smectite is of secondary importance in the Rose garden and soil on the SE boundary. X-ray diffraction (XRD) diagrams are presented in Appendix 5. The sample composed entirely of undecomposed leaf litter (110.9.1) was omitted from XRD analysis because it lacked any mineral content.

Table 3-1 Results of X-Ray Diffraction (XRD) analysis and organic carbon on soil samples from the Royal Tasmanian Botanical Gardens (approximate weight %)

Sample	110.5.1	110.9.2
Location	Rose Garden Path	Natural Soil near SE boundary
Quartz	40±4	32±3
Organic		38±2
Plagioclase	19±3	7±2
Smectite	19±3	20±3
K-Feldspar	1±0.5	3±1
Halloysite	3±1	
Clinopyroxene	3±1	
Hematite	8±2	
Ilmenite	1±0.5	
Laumontite	4±1	
Stilbite	1±0.5	
Apatite	1±0.5	

A range of results was given for each mineral detected, to compensate for a possible 'peak overlap' that may interfere with identifications and quantitative calculations; such as can occur between Potassium Feldspar and Clinopyroxene.

Amorphous material and trace amounts of minerals not detected are shown as blanks.

3.2 Organic carbon and sulfur

Table 2-2 contains the results of NDIR analysis of soils undertaken at MRT. Organic content of soil samples was calculated using NDIR measurements. No sulphur-containing minerals were identified in any sample. Due to its lack of mineral content, the soil sample composed entirely of undecomposed leaf litter (110.9.1) was omitted from NDIR analysis.

The Carbon contents were converted to approximate Total organic matter, by multiplying the total organic carbon content by 1.7, a standard figure (Howard, 1965).

Small Sulfur contents were noted in most samples but no Sulfur-bearing species were identified; appearing to correlate with organic matter.

Table 3-2 Nondispersive Infrared Analysis (NDIR) of Carbon and Sulfur Content of soils from the Royal Tasmanian Botanical Gardens (RTBG

Sample	**Location**	**Carbon (%)**	**Sulphur (%)**	**Analyses**
110.5.1	**Anthropogenic soil from Rose Garden Path in RTBG**	0.70	0.09	2
110.9.2	**Natural soil near SE boundary of RTBG**	22.8	0.54	3

Standards run during analyses to check calibration: AR4005 (C=1.42%, S=1.41%), AR4013 (C=2.93%, S=0.020%), AR4014 (C=5.87%, S=0.029%), AR4007 (C=7.27%, S=3.26%) and AR4024 (C=11.72%, S=0.418%)

4. IMAGE PROCESSING CONDUCTED ON DIGITAL PHOTOGRAPHS TAKEN OF SOIL TRANSFER PATTERNS

Image processing software analysed digital photos taken of every soil transfer experiment (STE). Quantifiable statistics were collected regarding the abundance of soil transferred, percentage of individual soil objects and aggregates, Munsell soil colour range and directionality of soil transferred. These statistics were then combined by soil sample, method of transfer and whether soil was wet or dry when the test was run; producing the following graphs and Rose diagrams.

4.1 Abundance of soiled areas on fabric compared to clean areas of fabric

Soil objects recognised by image processing software as areas in pixels were categorised as pale smears, brown smears, organics as well as areas of clean fabric. Due to the software's difficulty in recognising organic objects, the true area of this category is not realistically represented in the following graphs (Figure 4-1 to Figure 4-4).

It must also be noted that the image processing software could not reliably recognise soil objects <100 microns. Anthroposol soil samples from the Rose Garden gravel path (110.5.1) produced marked differences in the area of clean fabric remaining if the fabric had been placed or dragged across the soil surface in the field. A wet soil surface produced a greater area of fabric with pale brown or dark brown smears (Figure 4-1).

These differences between placing and dragging fabric across soil in the field was dramatically increased; compared to fabric dragged across soil samples from the same location in laboratory experiments (Murray et al. 2016).

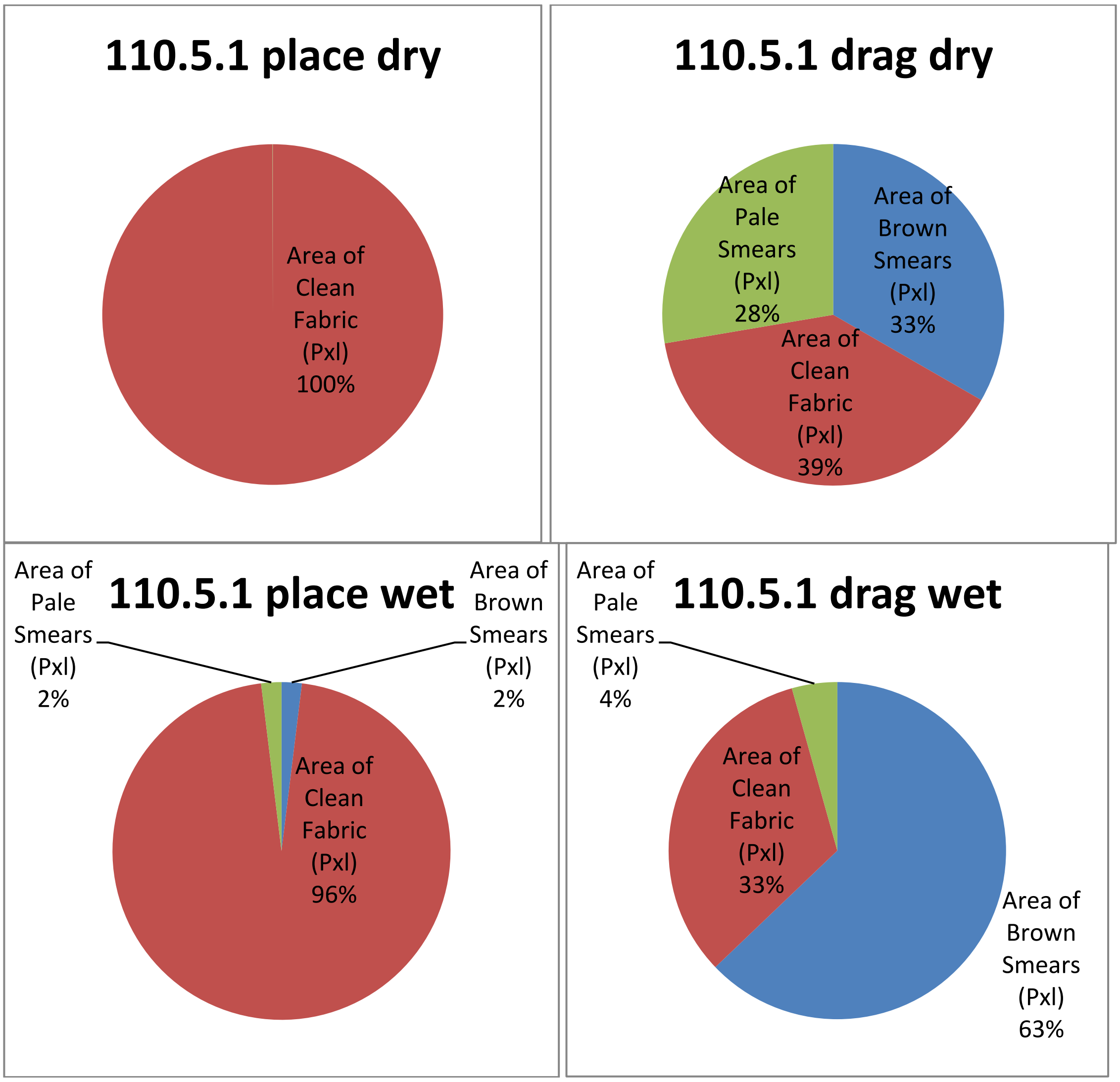


Figure 4-1 Abundance of dry and wet soil transferred to fabric from the Rose Garden path (110.5.1), RTBG. Image processing showed these results as areas in pixels.

Natural soil under deciduous tree leaves from the southeast boundary of the RTBG produced a similar difference in the abundance of soil transferred when wet or dry soil was used, as shown by the gravelly soil surface of the anthroposol Rose garden path (Figure 4-2). This natural soil was composed of undecomposed leaf litter (soil sample 110.9.1) covering dark organic-rich undisturbed soil (110.9.2). Using this natural soil sample, image processing software detected no soil transferred to the bra fabric area when the clothed body was placed on the dry soil surface. When this same soil surface was wet, 10% of the fabric had soil objects transferred. When the body was dragged across a dry soil surface, 89% of the bra fabric surface appeared clean; with any soil objects transferred being below 100 microns. When the soil surface was wet, only 45% of the bra fabric area was recognised as clean; with 55% of fabric analysed as soiled.

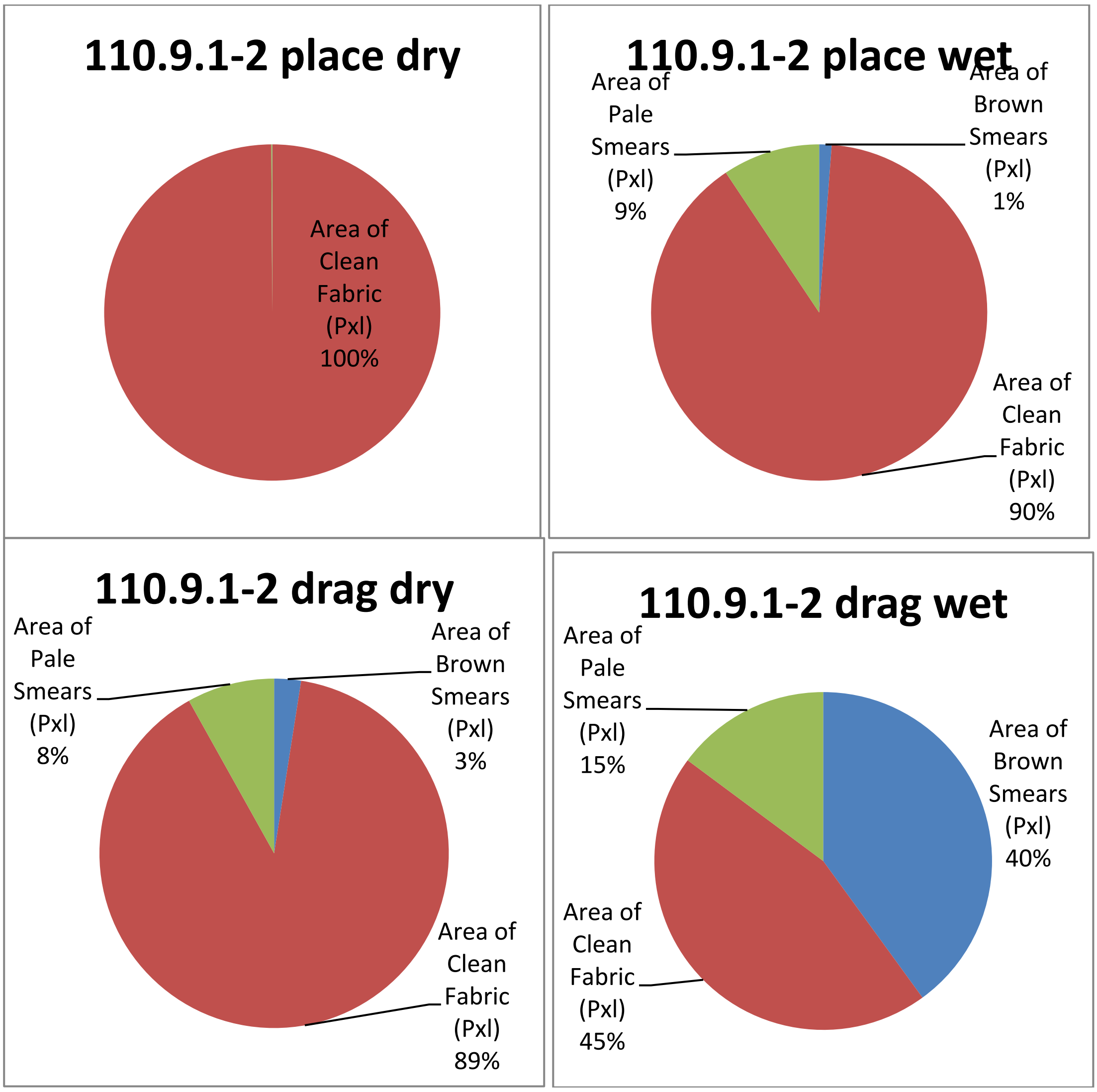


Figure 4-2 Abundance of dry and wet soil transferred to fabric from natural soil near the south eastern boundary fence (110.9.1-2), RTBG. Image processing showed these results as areas in pixels.

4.2 Individual soil objects and aggregates of soil objects transferred to fabric

Soil samples from the Rose Garden path (110.5.1) showed the transfer of 30-35% of individual soil objects and 70-65% of aggregates of soil objects onto bra fabric when placed on dry soil (Figure 4-3). When wet soil is used, 20-70% of individual soil objects and 80-30% of aggregates are transferred onto fabric.

When the rescue dummy is dragged across dry soil, bra fabric shows 10% of individual soil objects and 90% of soil aggregates transferred. When soil is wet, an overwhelming 98-100% of soil aggregates are transferred.

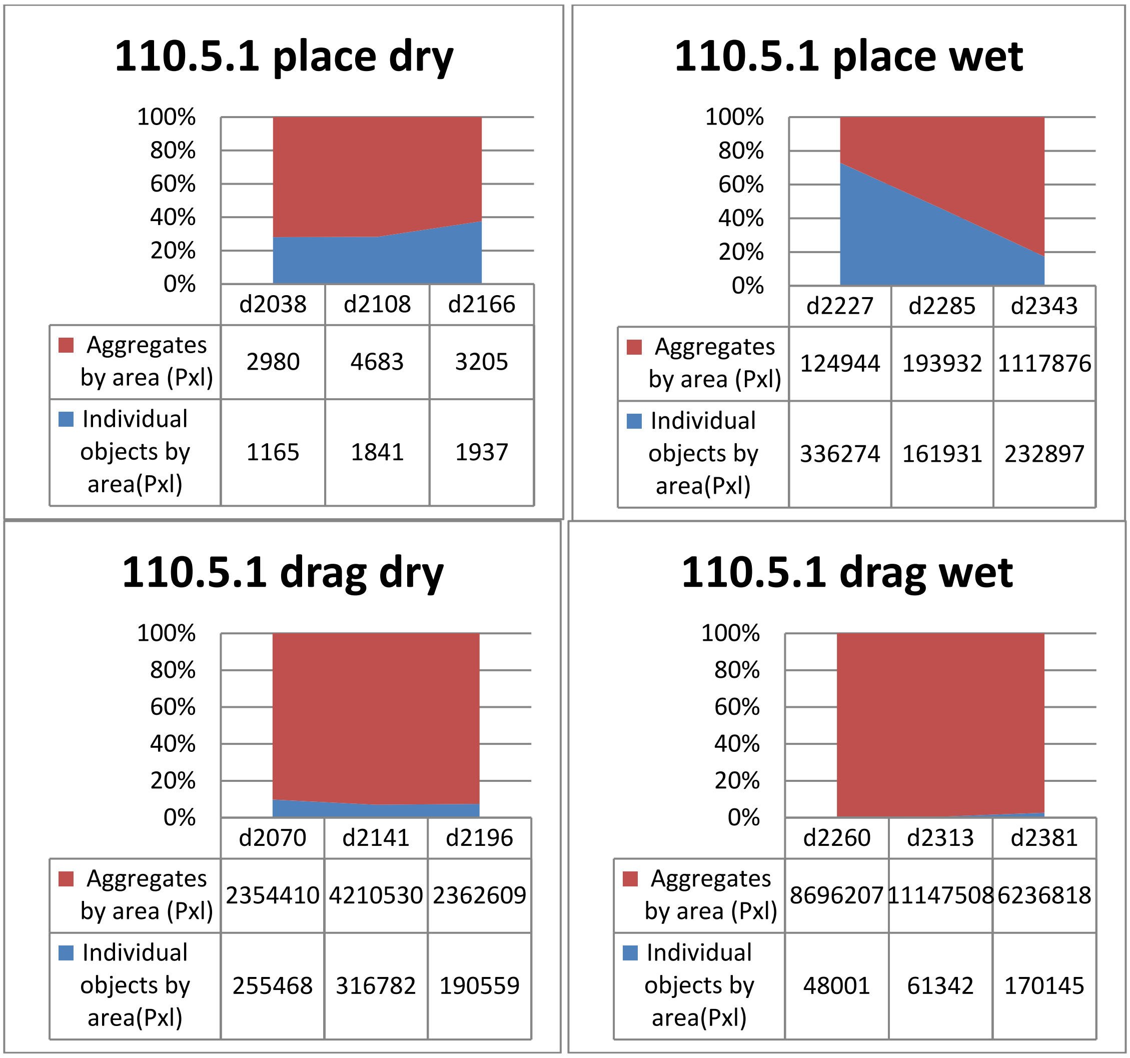


Figure 4-3 Individual soil objects and aggregates of soil objects transferred to fabric, shown as an area of pixels, from the Rose Garden path (110.5.1), RTBG.

The natural soil sample composed of leaf litter and organic soil (110.9.1-2) transferred 0-20% of individual soil objects and 100-80% of aggregates when the body was placed on dry soil; and 0-10% of individual objects and 100-90% of aggregates when soil was wet (Figure 4-4).

When the body was dragged across the dry natural soil surface, 8-25% of individual soil objects 92-75% of soil aggregates were transferred to the bra fabric. When soil was wet, 5-12% of individual soil objects and 95-88% of aggregates were transferred to bra fabric.

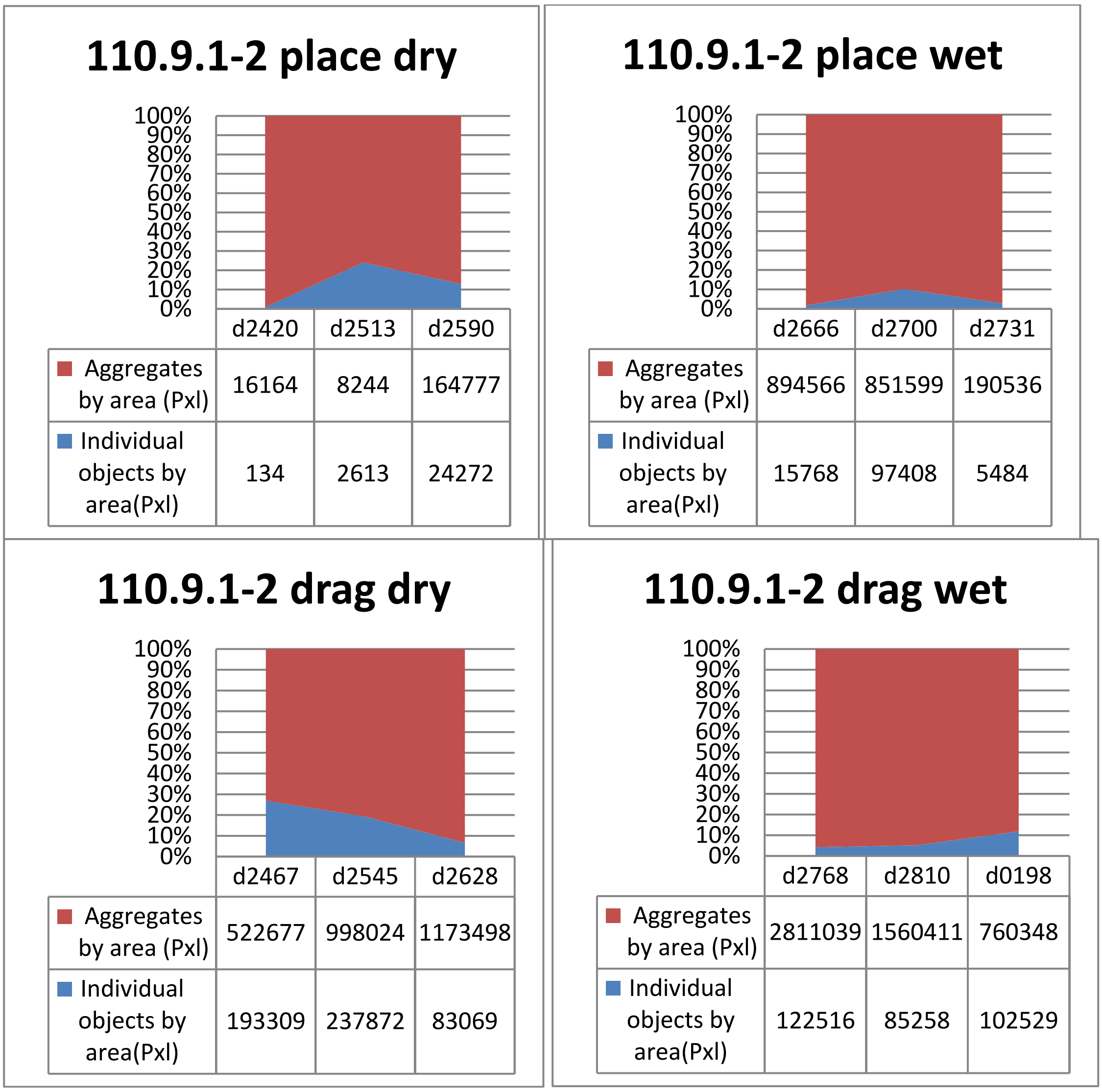


Figure 4-4 Individual soil objects and aggregates of soil objects transferred to fabric, shown as an area of pixels; from natural soil under trees from the southeast boundary of RTBG, composed of leaf litter (110.9.1) and undisturbed organic-rich soil (110.9.2).

5. Soil Transference patterns identified in STEs using the transfer methods of placing and dragging

SOIL TRANSFERS:		Bra-strap &/or cup						
CAFSS no.	Run	Sediment trails strap/cup	Elongate fragments aligned	Raised or folded seam sed build-up	Fabric speckled with sed	Damaged or frayed fabric	Fold & crease marks	Wet: Water stains
PLACEMENT	Dry 1	X	X	X	√	X	X	N/A
CAFSS_	Dry 2	X	X	X	√	X	X	N/A
110.5.1	Dry 3	X	X	√	√	X	X	N/A
Rose Garden	Wet 1	X	X	√	√	X	X	√
Path	Wet 2	X	X	√	√	X	X	√
	Wet 3	X	X	√	√	X	X	√
% occurrence	Dry	0%	0%	33.3%	100%	0%	0%	N/A
CAFSS_110.5.1	Wet	0%	0%	100%	100%	0%	0%	100%
PLACEMENT	Dry 1	X	X	X	√	X	√	N/A
CAFSS	Dry 2	X	X	X	√	X	X	N/A
110.9.1	Dry 3	X	X	X	√	X	X	N/A
Natural	Wet 1	X	X	√	√	X	X	√
Soil	Wet 2	X	X	√	√	X	X	√
	Wet 3	X	X	√	√	X	X	X
% occurrence	Dry	0%	0%	0%	100%	0%	33.3%	N/A
CAFSS_110.9.1	Wet	0%	0%	100%	100%	0%	0%	66.6%
DRAG	Dry 1	√	X	√	X	√	√	N/A
CAFSS_	Dry 2	√	√	√	X	√	√	N/A
110.5.1	Dry 3	√	√	√	√	√	√	N/A
Rose Garden	Wet 1	√	X	√	√	√	√	√
Path	Wet 2	√	X	√	X	√	√	√
	Wet 3	√	X	√	√	√	√	√
% occurrence	Dry	100%	66.6%	100%	33.3%	100%	100%	N/A
CAFSS_110.5.1	Wet	100%	0%	100%	66.6%	100%	100%	100%
DRAG	Dry 1	√	√	√	X	X	√	N/A
CAFSS_	Dry 2	√	√	√	X	X	X	N/A
110.9.1	Dry 3	√	√	√	√	X	√	N/A
Natural	Wet 1	√	X	√	X	X	√	√
Soil	Wet 2	√	√	√	X	X	X	X
	Wet 3	√	X	√	X	X	√	X
% occurrence	Dry	100%	100%	100%	33.3%	0%	66.6%	N/A
CAFSS_110.9.1	Wet	100%	33.3%	100%	100%	0%	66.6%	33.3%
KEY:								
√ = pattern occurs on bra-strap and/or cup								
X = pattern does not occur on bra-strap or cup								
N/A = Not applicable								

continued...

SOIL TRANSFERS:		Bra-strap only				
CAFSS no.	Run	Strap edge sediment build-up	Buckle sed build-up	Fluffy seam sed build-up	Dry: Dusting sed evenly over buckle	Wet: buckle clean &/or mud clumps
PLACEMENT	Dry 1	X	X	X	X Clean	N/A
CAFSS_	Dry 2	X	X	√	X Clean	N/A
110.5.1	Dry 3	X	X	X	X Clean	N/A
Rose Garden	Wet 1	√	X	√	N/A	√
Path	Wet 2	√	√	√	N/A	√
	Wet 3	√	X	√	N/A	√
% occurrence	Dry	0%	0%	66.6%	0%	N/A
CAFSS_110.5.1	Wet	100%	33%	100%	N/A	100%
PLACEMENT	Dry 1	X	√	X	√	N/A
CAFSS	Dry 2	√	X	√	√	N/A
110.9.1	Dry 3	X	√	√	√	N/A
Natural	Wet 1	X	X	X	N/A	√
Soil	Wet 2	X	√	X	N/A	√
	Wet 3	X	X	X	N/A	√
% occurrence	Dry	66.6%	100%	66.6%	33.3%	N/A
CAFSS_110.9.1	Wet	33.3%	33.3%	0%	N/A	100%
DRAG	Dry 1	√	√	√	X	√
CAFSS_	Dry 2	√	√	√	X	√
110.5.1	Dry 3	√	√	√	X	√
Rose Garden	Wet 1	√	√	√	N/A	√
Path	Wet 2	√	√	√	N/A	√
	Wet 3	√	√	√	N/A	√
% occurrence	Dry	100%	100%	100%	0%	100%
CAFSS_110.5.1	Wet	100%	100%	100%	N/A	100%
DRAG	Dry 1	√	√	X	√	N/A
CAFSS_	Dry 2	√	√	√	√	N/A
110.9.1	Dry 3	√	√	√	√	N/A
Natural	Wet 1	√	√	√	N/A	√
Soil	Wet 2	√	√	√	N/A	√
	Wet 3	√	√	√	N/A	√
% occurrence	Dry	1005	100%	66.6%	100%	N/A
CAFSS_110.9.1	Wet	100%	100%	100%	N/A	100%

KEY:

√ = pattern occurs on bra-strap and/or cup

X = pattern does not occur on bra-strap or cup

N/A = Not applicable

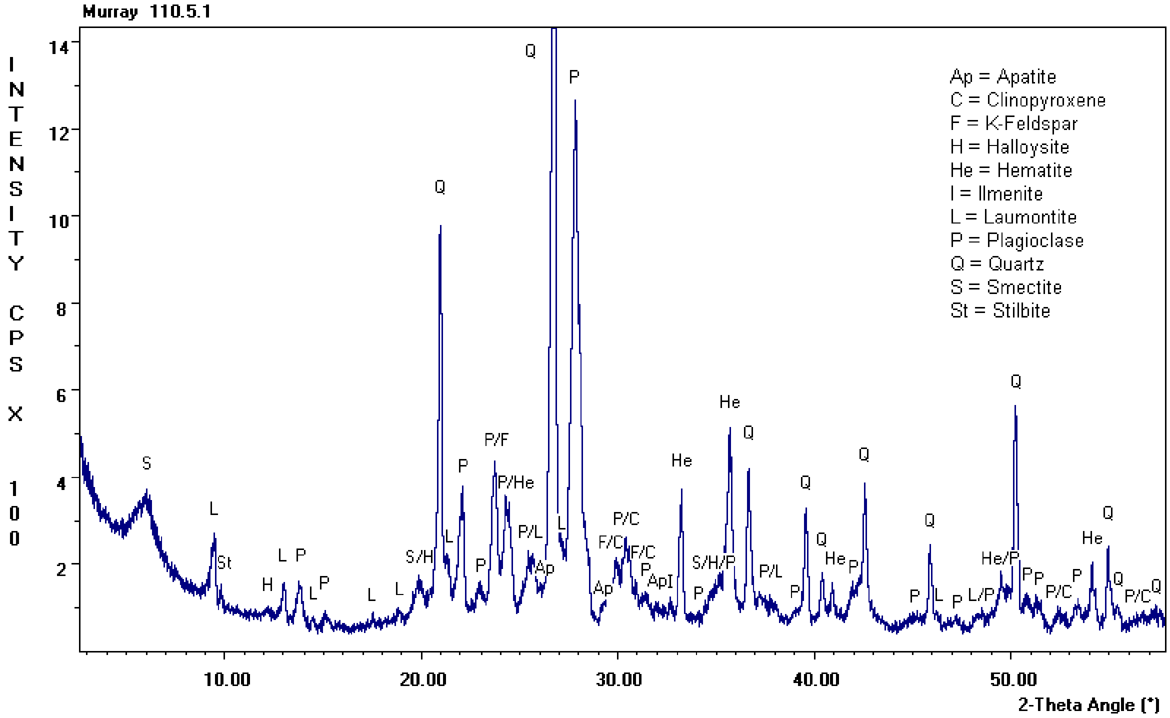
6. Image processing statistics showing Munsell colour range of soil samples shown as area in pixels

Soil	Soil	Soil	Digital	Munsell colour range (Area of each colour in pixels)											
Sample	Transfer	Moisture	Photo	2.5YR				7.5YR							
no.	Method	content	no.	3/1	5/8	6/1	7/8	2.5/1	2.5/2	3/2	3/4	4/6	5/2	5/6	6/6
110.5.1	place	dry	d2038	0	0	5732	0	0	83899	0	15775	0	13684	0	0
110.5.1	place	dry	d2108	0	0	8750	0	0	228112	0	0	2440	60962	0	0
110.5.1	place	dry	d2166	0	0	6789	0	0	188156	0	0	0	44289	0	0
110.5.1	drag	dry	d2070	0	0	235008	0	0	13218	0	0	0	0	0	0
110.5.1	drag	dry	d2141	0	0	242406	0	0	0	0	0	0	0	0	0
110.5.1	drag	dry	d2196	0	0	240977	0	0	53634	0	0	0	0	0	0
110.5.1	place	wet	d2227	0	0	69038	0	0	166264	0	0	6464	41733	0	0
110.5.1	place	wet	d2260	0	0	40436	0	1591	402730	0	167384	16476	169387	0	0
110.5.1	place	wet	d2285	0	0	55983	0	0	207037	0	0	11085	62463	0	0
110.5.1	drag	wet	d2313	0	0	69331	0	0	142976	0	114182	39441	89902	0	0
110.5.1	drag	wet	d2343	0	0	142858	0	1057	94635	0	0	3496	40390	0	0
110.5.1	drag	wet	d2381	0	0	104399	0	0	188498	0	88965	43500	96584	0	0
110.9.1-2	place	dry	d2420	0	0	3631	0	0	172301	72430	265140	0	24288	0	0
110.9.1-2	place	dry	d2513	0	0	15928	0	0	49526	0	21460	0	3225	0	0
110.9.1-2	place	dry	d2590	0	0	41417	0	3416	282676	45342	402354	11257	76057	0	0
110.9.1-2	drag	dry	d2467	55	0	185060	0	0	1460805	43857	33458	0	283498	0	0
110.9.1-2	drag	dry	d2545	0	0	223183	62	0	444300	0	0	0	15672	0	0
110.9.1-2	drag	dry	d2628	0	0	234362	0	0	141061	0	180923	0	37738	0	0
110.9.1-2	place	wet	d2666	0	0	37458	0	0	99017	0	74889	8913	41274	0	0
110.9.1-2	place	wet	d2700	0	0	71434	0	0	436962	0	0	0	18452	0	0
110.9.1-2	place	wet	d2731	0	0	28179	0	0	277622	0	0	0	30155	0	0
110.9.1-2	drag	wet	d2768	0	0	190728	2064	0	24497	0	420365	96342	20843	71103	101978
110.9.1-2	drag	wet	d2810	0	0	114326	630	0	104191	23502	228457	51897	27410	17897	11976
110.9.1-2	drag	wet	d0198	4	0	92606	0	68216	1152272	1482014	1837810	0	210599	0	0

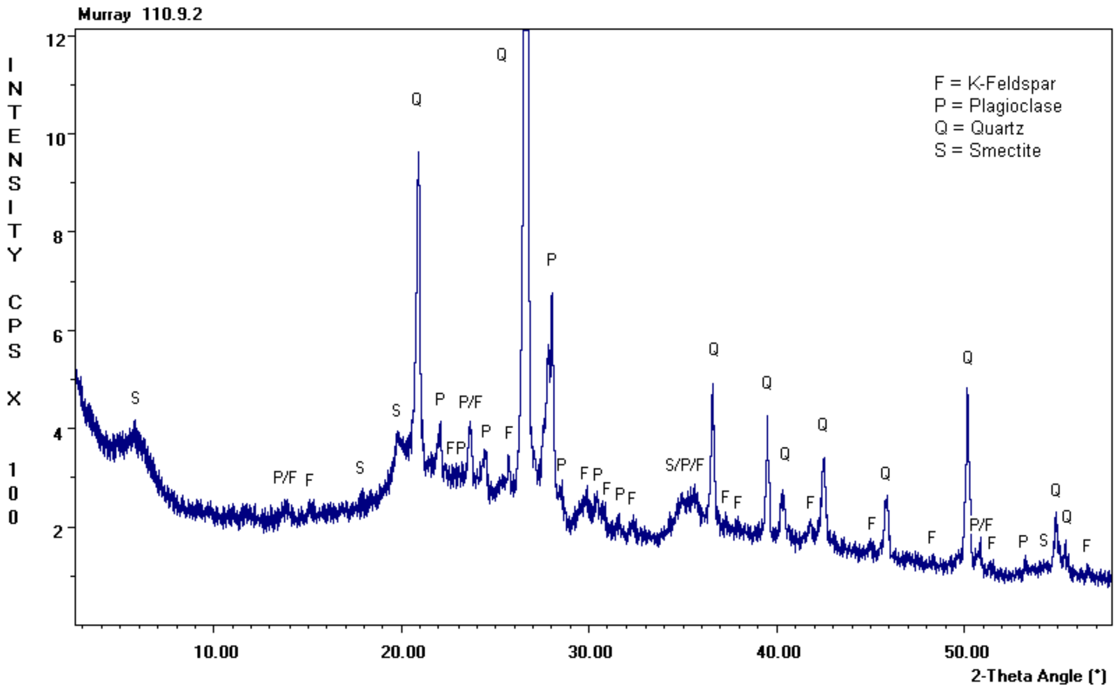
Soil	Soil	Soil	Digital	Munsell colour range (Area of each colour in pixels)												
Sample	Transfer	Moisture	Photo	10YR												
no.	Method	content	no.	2/1	2/2	3/1	3/2	4/2	4/3	5/2	5/3	5/4	6/3	6/4	6/6	7/2
110.5.1	place	dry	d2038	0	0	0	0	15574	1334	3868	0	0	28670	0	0	0
110.5.1	place	dry	d2108	0	0	0	0	18041	7102	10253	10720	1463	63404	0	0	32952
110.5.1	place	dry	d2166	0	0	0	0	8634	5406	8788	4113	3249	28533	0	0	0
110.5.1	drag	dry	d2070	0	0	0	0	0	0	0	0	0	62254	13111	0	631896
110.5.1	drag	dry	d2141	0	0	0	0	0	0	0	6055	0	123608	3146	0	515379
110.5.1	drag	dry	d2196	0	0	0	0	0	0	0	0	0	20891	0	0	412316
110.5.1	place	wet	d2227	0	0	0	0	0	0	0	10109	1569	362136	0	0	327536
110.5.1	place	wet	d2260	0	0	0	0	6194	100830	6531	134622	42885	77327	0	0	4955
110.5.1	place	wet	d2285	0	0	0	0	6727	0	3028	32353	2792	258699	0	0	122264
110.5.1	drag	wet	d2313	0	0	0	0	0	18036	0	91763	15327	749209	0	0	231683
110.5.1	drag	wet	d2343	0	6746	0	0	0	0	0	11090	2413	401583	0	0	464077
110.5.1	drag	wet	d2381	0	0	0	0	0	0	0	317899	43202	273559	866	0	189901
110.9.1-2	place	dry	d2420	0	0	0	24825	16701	24855	10487	9224	1976	37211	0	0	5207
110.9.1-2	place	dry	d2513	0	0	0	0	5970	2849	0	0	0	3889	0	0	0
110.9.1-2	place	dry	d2590	0	0	0	0	21033	46124	57157	56809	3077	120419	0	0	118887
110.9.1-2	drag	dry	d2467	0	0	0	0	45330	2429	33006	0	0	63011	0	0	135907
110.9.1-2	drag	dry	d2545	0	0	0	0	0	0	0	0	657	94412	3366	0	63130
110.9.1-2	drag	dry	d2628	0	0	0	0	17492	18659	35887	3087	619	101958	0	0	332690
110.9.1-2	place	wet	d2666	0	0	0	0	32192	31459	24060	22473	640	142197	1933	0	275698
110.9.1-2	place	wet	d2700	0	0	0	0	3148	3078	19671	4680	1011	49496	0	0	11157
110.9.1-2	place	wet	d2731	0	0	0	0	30440	0	37620	11860	352	72080	0	0	0
110.9.1-2	drag	wet	d2768	0	0	0	0	0	0	0	55057	18817	278664	61249	0	1598092
110.9.1-2	drag	wet	d2810	0	0	0	0	6440	3311	11068	31090	3698	284043	39724	0	409954
110.9.1-2	drag	wet	d0198	0	19351	0	335709	153801	61194	137721	20375	1164	130562	0	0	51022

7. X-ray diffraction (XRD) patterns

Soil no. 110.5.1	*Site 5 RTBG, Rose Garden path*	Queens Domain, Hobart	Dark brown Soil
Soil no. 110.9.2	*Site 9 RTBG, Natural soil*	Queens Domain, Hobart	Very dark brown Soil



Sample no. 110.5.1: Site 5 Rose Garden path, RTBG, Queens Domain, Hobart. Dark brown Soil



Sample no. 110.9.2: Site 9 Natural soil SE boundary, RTBG, Queens Domain, Hobart. Very dark brown soil

7.3 Online article: Using soil color analysis for forensic application at a crime scene

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Using Soil Color Analysis for Forensic Application at a Crime Scene

We interviewed forensic soil scientist Kathleen Murray to talk about her study: *Soil Transference Patterns on Bras: Image Processing and Laboratory Dragging Experiments*.

What is forensic soil analysis?

Forensic soil analysis is used by forensic soil experts and police forensic investigators to provide evidence to help police solve crime. In major crimes with no fingerprint or DNA evidence or reliable witness testimony, soil evidence can help police target their enquiries towards a particular suspect or location. Soil evidence can be even more valuable when it enhances other supporting evidence.

Trace soil evidence is often overlooked by criminals trying to remove all evidence of their crime. When two surfaces come into contact, such as shoes or clothing belonging to a victim/suspect and a soil surface, there is potential for the mutual transfer of minute traces of material between them. Forensic soil scientists use different methods to analyse this soil evidence including visual analysis, light microscopy, Scanning Electron Microscopy and X- Ray Diffraction analysis.

How was it applied in this study?

The current approach to analyzing forensic soil evidence is to focus on profiling the chemistry of the soil to indicate a possible origin. Because of this focus, police photographs are not generally taken of soil mark/pattern evidence on suspects/victim's clothing at the crime scene; before the body is moved or clothing removed. Instead, soil evidence is generally ignored until specific items are chosen for analysis by either police forensic investigators or forensic soil experts. This soil analysis begins once as much soil as possible is rigorously removed from clothing fabric. This removal may involve shaking soil particles from clothing into collection bags or even cutting out sections of soiled material. Not since Locard's experiments in 1930 has anyone published methods to help police use soil marks/patterns on clothing to interpret what happened to a victim during or after a crime.

The aim of this research was to test whether soil patterns on fabric could provide police with a reliable method to interpret trace soil pattern evidence on clothing. During my research (some papers yet to be published), two methods of soil transfer have been tested; namely placing or dragging a simulated clothed human victim across a soil surface. Resulting trace soil patterns were analysed with 'naked eye' visual analysis and light microscopy. All soil samples underwent XRD analysis to test whether soil chemistry and mineralogy had influenced the resulting soil patterns on clothing fabric.

Soil evidence was analyzed for Munsell soil color using both a traditional naked eye technique and a new method I developed involving image processing analysis of digital photos of trace soil evidence on clothing. Trimble eCognition Developer image processing software was programmed to recognize a limited palette of 25 Munsell soil colors. Digital photographs of soil evidence on white clothing fabric was then analyzed to ascertain whether image processing software had the potential to offer police a more objective and accurate method of analyzing Munsell soil color than naked eye visual analysis and a cheaper, quicker and more accessible method than spectrophotometry.

Why was it so important for this case?

This research was instigated by a high-profile unsolved murder case from Western Australia. In this murder case, the only forensic evidence was soil evidence on the victim's clothing and boots. The victim's husband was put on trial but acquitted for her murder. Because of the lack of published papers that offered a scientific interpretation of trace soil patterns on clothing, the judge could not accept the police interpretation of what happened to the victim during or after the attack, beyond reasonable doubt.

Soil is comparable to a human fingerprint in its uniqueness. Why is that?

Soil will never be as uniquely individual as the patterns formed by ridgelines on a human fingerprint. Even identical twins have different fingerprint patterns. However, natural soil types are created from combinations of different parent rocks and organic materials, which undergo a large variety of geological and climatic processes to produce soil. The resulting soil will be relatively unique when compared with soil from different locations.

Human-altered or human-transported soil will often contain a combination of minerals or human-made items (such as glass or plastic particles) not normally found together in a natural environment. When soil samples from known locations are compared to unknown or 'suspect' trace soil evidence taken from shoes or clothing, similarities and differences in the unknown soil's minerals, chemistry, biology and physical characteristics are documented.

When only trace amounts of soil have been transferred to clothing, it can be technically challenging for forensic soil scientists to confirm the soil's origin.

Describe your role in the study.

Until this research was undertaken, there was no scientific method accepted in a court of law to interpret trace soil marks on items of clothing evidence. For my PhD project, I designed a series of soil transfer experiments, run both in the laboratory and field, to simulate a clothed human body either placed or dragged across a soil surface. After initially running experiments in the laboratory, I tested whether the trace soil marks identified under controlled laboratory conditions could also be documented under realistic conditions in the field. In this second series of experiment (in a paper soon to be published), a human rescue dummy dressed in a clean padded bra was dragged across different soil surfaces in the Royal Tasmanian Botanical Gardens in Hobart, Tasmania.

How did you choose which types of soils to use in the study?

Natural and human-made or human-altered Tasmanian soil samples were used in this study;

to increase scientific understanding of how trace soil evidence that had originated from local soil sites would appear on different common clothing fabrics. (Although only one fabric types was investigated in this paper [Murray et al. (2016)], different common fabric types were tested in papers yet to be published).

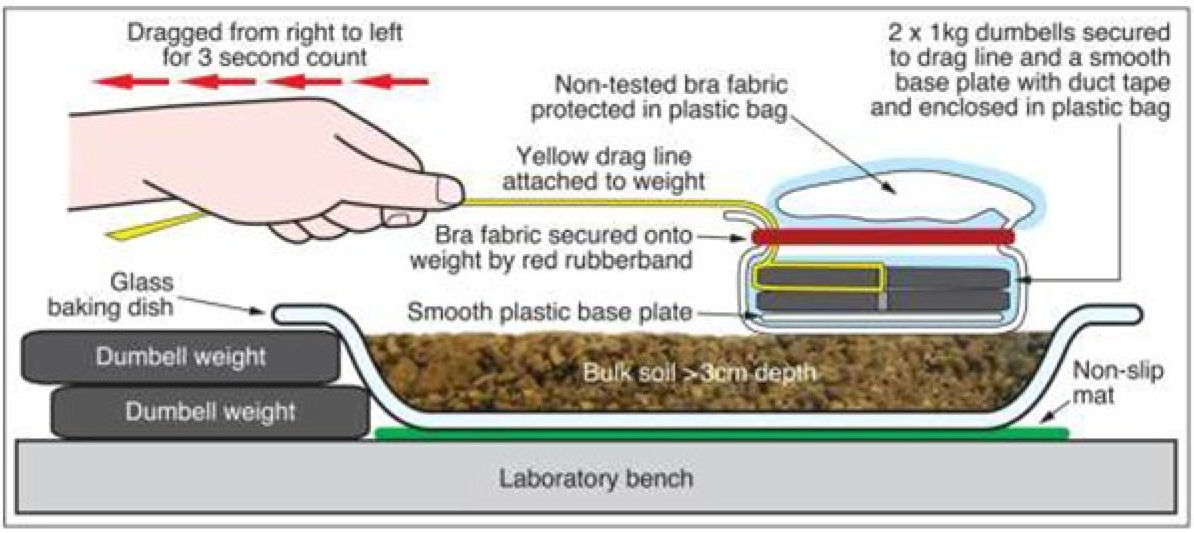
Summary Table of Soil Morphology and Selected Chemical Properties

Locality	Sample no.	Matrix colour Dry	Matrix colour Moist	Texture	Gravel >2mm%	Quartz	Structure	Efferv. Class	Roots	WR	pH distill H20	pH CaCl2
Rose Garden Path	110.5.1	7.5YR 5/2 Brown	7.5YR 3/2 Dark brown	LS	90	R - S	Granular to single grain	NE	0	R	7.03	6.16
Rose Garden path near wall	110.6.1	7.5YR 5/2 Brown	7.5YR 3/2 Dark brown	S	90	R	Granular to single grain	NE	0	N	7.71	7.05
Brick fragments	110.6.2	2.5YR 7/8 Light red	2.5YR 5/8 Red	Brick	90	R - UT	Brick fragments & br. Dust	NE	0	N to R	N/A brick	N/A brick
Rose Garden bed	110.7.1	7.5YR 2.5/1 Black	10YR 2/1 Black	LS	15	R	Massive	NE	1	R	6.49	5.81
Japanese Garden	110.8.1	2.5YR 6/1 Reddish gray	2.5YR 3/1 Dark reddish gray	LS	90	R - A	Granular to single grain	NE	0	R	6.27	5.53
Natural soil (leaf litter)	110.9.1	leaves	leaves	Undecom-posed leaves	2	N/A	Undecom-posed leaves	NE	0	R	N/A leaves	N/A leaves
Natural Soil	110.9.2	7.5YR 2.5/2 Very dark brown	10YR 2/2 Very dark brown	LS	2	R - S	Massive	NE	0	R	6.86	6.54

Texture: S, Sand; LS, Loamy Sand; obtained by the "feel" method in accordance with McDonald and Isbell (McDonald and Isbell 2009). Quartz = Quartz particles shape (Roundness and Sphericity): R = Rounded; S = Subrounded; UT = Subrounded tabular; A = Angular (McDonald and Isbell 2009). Effervescence Class (H4) (Reaction to 6N HCl): NE = Non effervescent; (Schoeneberger et al. 2002). Water Repellence (WR): N = Non water repellent; R = water repellent (McDonald and Isbell 2009). Roots: 0 = None; 1 = few (1-10 fine roots) in sample area $100mm^2$ (McDonald and Isbell, 2009; p.199).

The bras were dragged across the soil surface for three seconds. How did you determine this to be the appropriate amount of time?

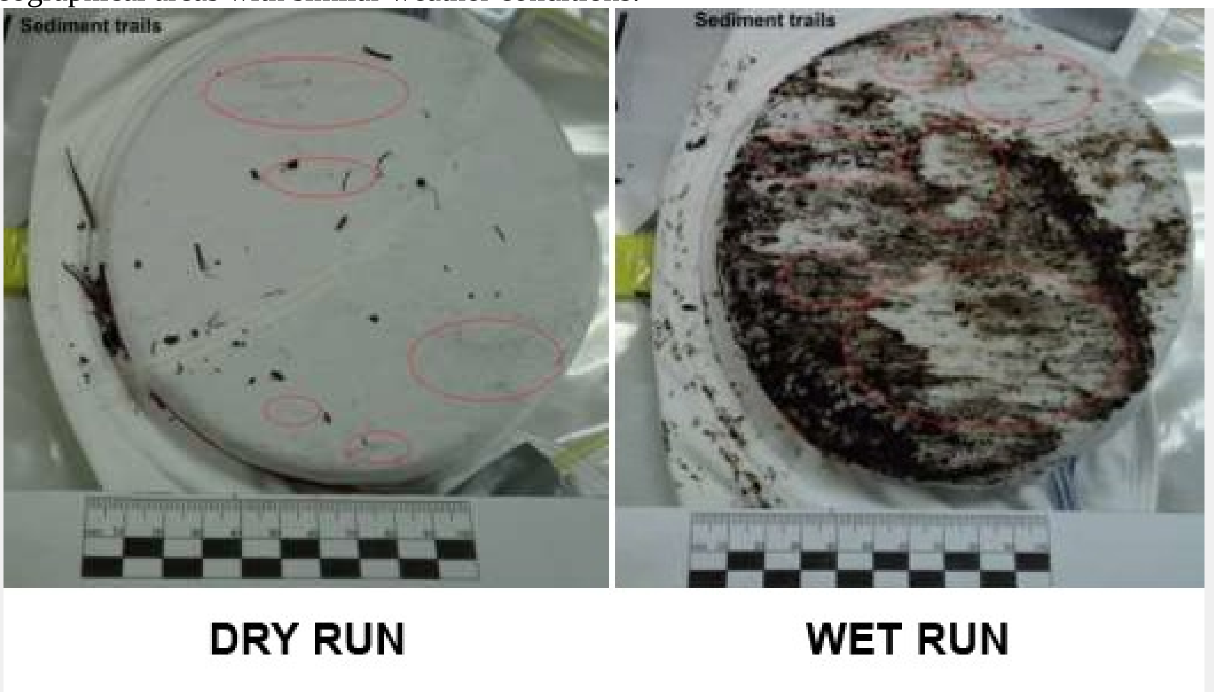
Three seconds was chosen as the optimum dragging time because of the dimensions of the glass Pyrex dish used in laboratory experiments. Each bra was secured to a weight and manually dragged in a straight line across the dish, using a drag line. To provide consistent and reproducible results, it was important that a continual dragging movement was achieved without any stopping or starting. It was also important that each 'run' moved at a controlled pace, without the need to rush. I personally found that three second dragging 'runs' enabled me to produce the most consistent results.



Cross-section of weighted bra dragged from right to left over soil material during a three second count soil transference experiment. Sections of bra that are not subjected to being dragged over the soil during the experiment remain clean inside a cliplock plastic bag on top of the weight. Note the end of the glass Pyrex dish containing soil material and weighted bra is placed on a nonslip mat and a backstop of weights on the left to stop it moving during the transference experiment.

What was unique about the soil transfer patterns?

During a series of soil transfer experiments, it was discovered that certain transfer patterns indicated whether soil had been transferred onto weighted clothing fabric either by dragging or placing a clothed victim on a soil surface. One soil pattern that strongly indicated a clothed victim had been dragged across soil was what I called 'soil trails'. Like tyre 'skid marks' on a road, straight lines of soil particles on fabric indicated that an unmoving clothed victim (possibly dead, drugged, unconscious or bound) was dragged across a soil surface. It was also discovered that soil marks could indicate whether soil was wet or dry at the time it was transferred. Knowing the moisture content of trace soil might help police to narrow the time slot in which the crime was committed. Or in the event that a body was moved to a second location and the first crime scene location was not known, forensic investigators may be able to use meteorological records to focus their search on geographical areas with similar weather conditions.



Soil trails on fabric, aligned with direction of movement right to left. The dramatic difference that can occur when soil from the same soil sample is transferred during a dry run (a) and wet run (b) is shown using natural soil sample (110.9.2). Notice also the massive build-up of soil over the raised middle seam and the minimal amount of soil transferred directly behind it.

Does it become more difficult to detect patterns if the fabric is colored?

This research was the first time image processing software was used to examine trace soil evidence on clothing fabric. To make this task easier, white fabric was chosen to provide a visual contrast to the color of all soils tested and thereby make it easier to identify microscope traces of soil particles transferred to clothing fabric.

Because soil comes in such a variety of colors, a more accurate method of detecting minute quantities of soil on multi-colored or patterned fabric will need to be developed to be of practical use to forensic investigators. One method to achieve this might be to programme image processing software to first identify clean sections of different clothing fabric textures. This might entail taking a digital photograph of a clean section of an item of clothing evidence. Another photograph of a soiled section of this clothing evidence would then be analysed to enable image processing software to better detect changes or 'breaks' in fabric texture patterns; when microscopic gaps in a woven fabric have been impregnated with soil particles.

How were the Munsell charts used?

Munsell soil color charts are routinely used in the field by soil scientists to determine soil color. In fact, Munsell soil color charts are used routinely by forensic soil scientists and geologists in the field and laboratory in most forensic investigations involving soil as evidence. “Soil color” is included in standard guidelines for conducting criminal and environmental soil forensic investigations in Australia and elsewhere in the world (Fitzpatrick and Raven 2016). As a consequence, Munsell soil colors have been used to help solve several major crime investigations such as when soil color, together with X-ray diffraction analyses, played a major role to solve a double murder case in South Australia (see Table 3 in Fitzpatrick and Raven 2012). During this research, Munsell charts were used to determine the soil color of known soil samples by traditional ‘naked eye’ analysis. Image processing software was also programmed to recognize the dominant range of Munsell colors from digital photographs of trace amounts of soil transferred to clothing fabric.

Munsell Colour of Moist and Dry Fine Fractions of Soil Samples

Soil sample **Location**	**Munsell Fine <2mm (Moist)** Fine (dry)	**Munsell colour Fine <2mm (Moist)** Fine (dry)	**Moist**	Dry
110.5.1 RTBG, Rose Garden path	**7.5YR 3/2** 7.5YR 5/2	**Dark brown** Brown	 **7.5YR 3/2**	 7.5YR 5/2
110.6.1 RTBG, Rose Garden path near brick wall	**7.5YR 3/2** 7.5YR 5/2	**Dark brown** Brown	 **7.5YR 3/2**	 7.5YR 5/2
110.6.2 RTBG, Brick fragments near wall	**2.5YR 5/8** 2.5YR 7/8	**Red** Light red	 **2.5YR 5/8**	 2.5YR 7/8
110.7.1 RTBG, Rose Garden bed	**10YR 2/1** 7.5YR 2.5/1	**Black** Black	 **10YR 2/1**	 7.5YR 2.5/1
110.8.1 RTBG, Japanese Garden	**2.5YR 3/1** 2.5YR 6/1	**Dark reddish gray** Reddish gray	 **2.5YR 3/1**	 2.5YR 6/1
110.9.1 RTBG, Natural soil site	LEAVES	N/A	N/A	N/A
110.9.2 RTBG, Natural soil site	**10YR 2/2** 7.5YR 2.5/2	**Very dark brown** Very dark brown	 **10YR 2/2**	 7.5YR 2.5/2

How did the use of Munsell charts help the study?

Although other color systems exist, as a forensic soil scientist, I prefer the simple and direct visual method soil color analysis the Munsell color systems provides. Because this system of soil color analysis is globally recognized, adopting this method enabled the results of this research to be understandable and relevant to forensic soil scientists and forensic investigators worldwide.

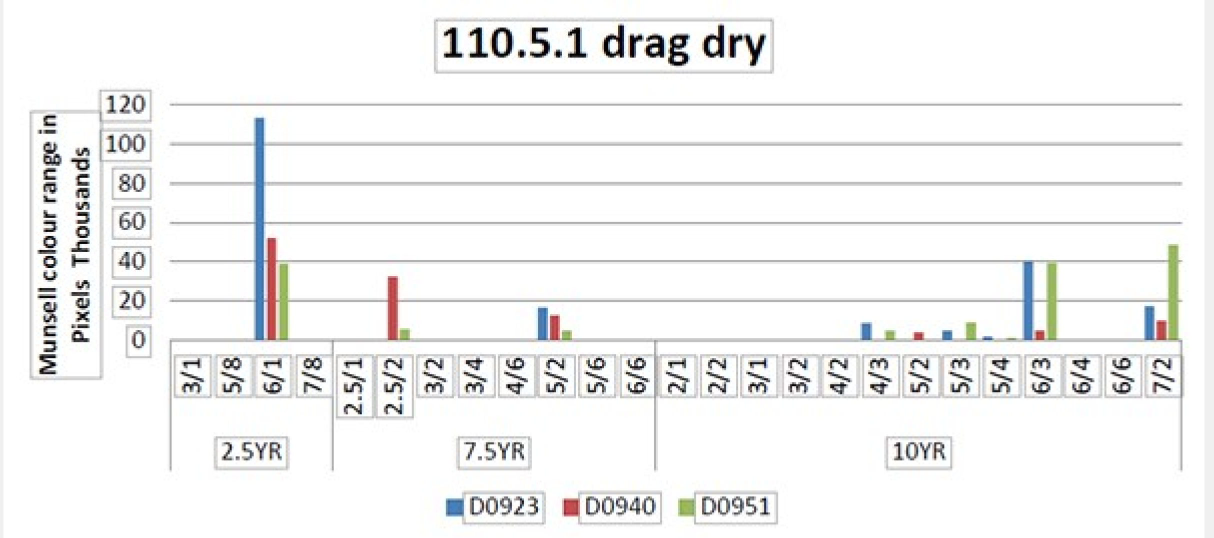
Why was the image processing analysis so important and how was it utilized in conjunction with the Munsell charts?

Image processing analysis was important in this study because every human retina is relatively unique and therefore soil color is not interpreted in exactly the same way by every soil scientist. It was hoped that image processing software could be programmed to provide a reliable and accessible method of objectively and accurately determining the Munsell soil color of trace amounts of soil evidence on clothing fabric. Although spectrophotometers have been designed to fulfill this purpose, they are not always accessible to forensic scientists analyzing soil evidence at crime scenes or in the laboratory.

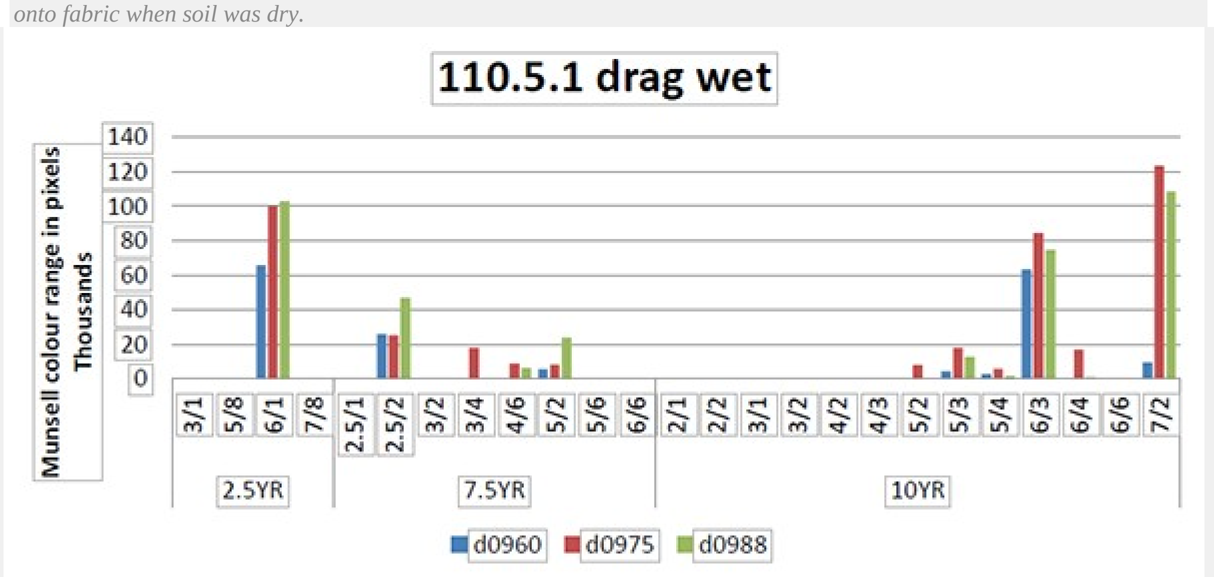
Image processing analysis also enabled a range of dominant Munsell soil colors to be identified for microscopic traces of soil evidence on clothing fabric. When image processing software was programmed to recognize a limited palette of Munsell soil colors, this resulted in dominant color peaks; reminiscent of mineralogical peaks seen in XRD analyses of soil evidence.

Image processing software was also programmed to identify the ‘directionality’ of individual soil particles greater than 2mm diameter. When this numerical data was graphed in a rose diagram, this provided a strong indication of whether soil had been transferred to clothing fabric by placing or dragging a clothed body on a soil surface.

Munsell Soil Colour Range of Soil Transferred to Fabric in Pixels



Munsell soil colour range recognised by image processing software of soil from the Rose garden path (110.5.1) transferred onto fabric when soil was dry.



Munsell soil colour range recognised by image processing software of soil from the Rose garden path (110.5.1) transferred onto fabric when soil was moist.

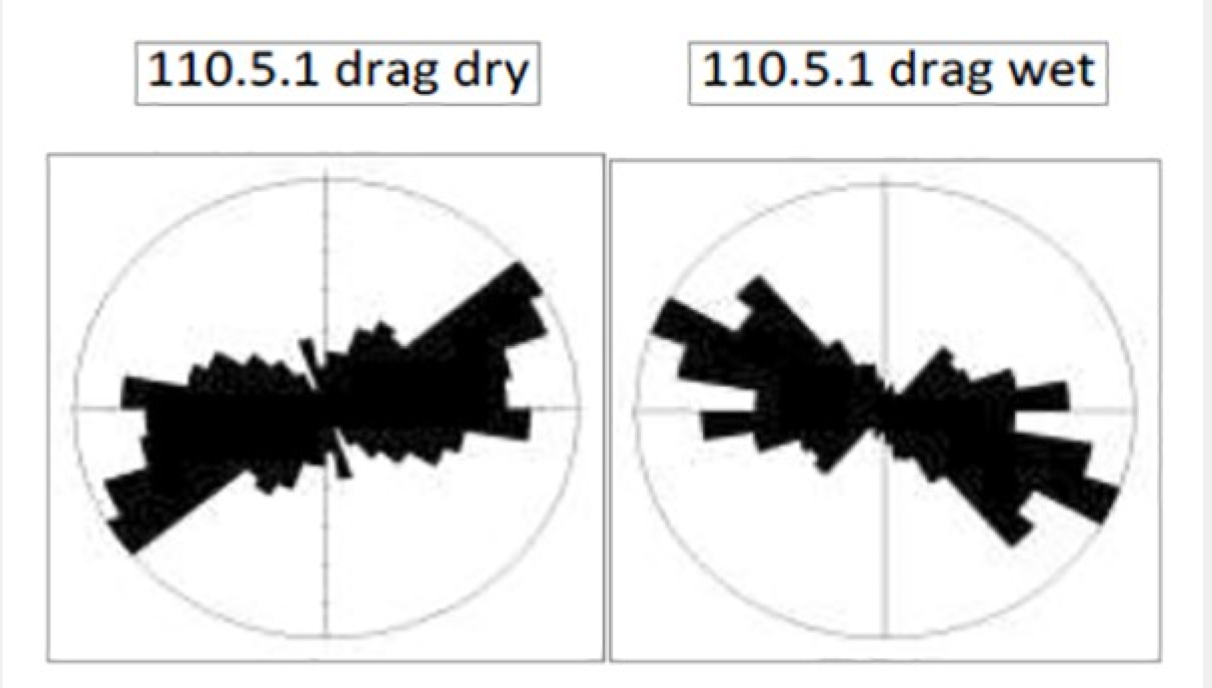
How can this study be used at a crime scene?

By taking digital photographs of soil evidence on a simulated clothed body under artificial lighting in a laboratory and natural lighting in the field, it was hoped image processing software could be programmed to adjust for different lighting conditions in order to identify trace soil evidence on clothing fabric, and specific characteristics such as soil color, using this photographic evidence alone.

Because trace soil patterns on clothing fabric can be easily disfigured or destroyed when a body is moved or clothing removed, two methods of recognising and recording trace soil evidence on clothing were developed; namely a visual 'naked eye' method and image processing. Most trace soil patterns could easily be identified by naked eye. However, digital photographs provided a pristine record of this soil evidence for further analysis.

For forensic laboratories facing a massive backlog of soil evidence waiting to be analysed, or police in developing nations who do not have access to expensive XRD machines, spectrophotometers or trained personnel required to interpret forensic soil results, pre-programmed image processing software may enable quick in-house testing of forensic soil evidence. If the Munsell color of trace soil evidence on a victim's clothing is analysed by image processing software as being very similar to soil evidence from a particular suspect's clothing or shoes, this may provide police with a targeted focus for immediate investigation.

Directional Numerical Data Provided by Image Processing Software



Rose diagrams of the directionality of dry and moist soil transferred onto fabric during STEs. Strong uni-modal directionality was produced when fabric was dragged from right to left across the soil surface. Dry soil particles had a greater tendency than wet soil to gather against the middle seam, creating more of a bi-modal directionality.

How can evidence like this be used in a court of law?

The concept of conducting and interpreting soil transference experiments on clothing for a specific purpose, as published in our SFI journal paper, provided the catalyst and confidence for my co-author Professor Rob Fitzpatrick to design and conduct a new series of specific soil transference experiments in regard to a cold murder case in South Australia. The results of his soil transference experiments, which involved conducting laboratory transference shaking experiments with clean strips of pajama-top fabric, used Scanning Electron Microscopy to verify that the mineral particles were dominantly on the surface of the pajama fabric. Whereas, in the questioned pajama-top swatches, the particles were deeply impregnated in gaps between fibres of the fabric; which likely originated under water with force being applied on the pajama top. This information, together with other soil mineralogical data, was used by Professor Rob Fitzpatrick as evidence in the South Australian Supreme Court.

Was there anything about the results of the study that surprised you?

When I was first asked to design a method for interpreting trace soil evidence on clothing as evidence of the circumstances of an attack, it was not known whether trace soil patterns could be identified, let alone reliably reproduced. Once I had successfully identified sets of trace soil patterns under laboratory conditions that could be used to establish that a clothed victim had been dragged across a soil surface, it was not known whether these same patterns could be identified in the field using a clothed human rescue dummy. (The results of this second set of experiments are soon to be published.) I was pleasantly surprised when the same trace soil patterns were also recognized on clothing fabric in the field. A new set of trace soil patterns were also documented when the human rescue dummy was only placed on soil and not dragged across it. This was the strongest indication that this new method of forensic soil analysis could be used by forensic soil scientists to help police solve crime.

Soil Sample no.	Soil Transfer Method	Soil moisture content	Digital Photo no.	Munsell colour range (Area of each colour in pixels)											
				2.5YR				7.5YR							
				3/1	5/8	6/1	7/8	2.5/1	2.5/2	3/2	3/4	4/6	5/2	5/6	6/6
110.5.1	drag	dry	d0923	0	0	113331	0	0	0	0	0	0	16651	0	0
110.5.1	drag	dry	d0940	0	0	52037	0	0	32448	0	0	0	12597	0	0
110.5.1	drag	dry	d0951	0	0	38887	0	0	5529	0	0	0	4904	0	0
110.5.1	drag	wet	d0960	0	0	65695	0	0	25942	0	0	0	5576	0	0
110.5.1	drag	wet	d0975	0	0	99924	0	0	25270	0	17954	8807	8261	0	0
110.5.1	drag	wet	d0988	0	0	102981	0	0	46754	0	0	6223	23886	0	0
110.6.1	drag	dry	d1146	32	0	43993	0	0	107462	0	0	0	6899	0	0
110.6.1	drag	dry	d1172	0	125	79130	0	0	5010	0	0	0	7656	0	0
110.6.1	drag	dry	d1193	0	0	47210	0	0	45549	0	16994	0	2969	0	0
110.6.1	drag	wet	d1220	0	0	85460	0	0	0	0	0	16201	15990	0	0
110.6.1	drag	wet	d1241	0	0	68460	0	0	5688	0	19828	14486	23145	0	0
110.6.1	drag	wet	d1260	0	0	84324	0	0	20232	0	0	0	7040	0	0
110.6.2	drag	dry	d1840	0	263	121548	241	0	22703	0	0	5074	0	0	41318
110.6.2	drag	dry	d1865	0	263	94715	0	0	18640	0	0	0	5234	0	10642
110.6.2	drag	dry	d1889	0	0	62224	27	0	0	0	0	0	0	0	0
110.6.2	drag	wet	d1912	0	0	88272	40	0	11324	0	0	2324	0	9609	0
110.6.2	drag	wet	d1934	0	151	124520	956	0	53400	0	0	0	4812	0	8766
110.6.2	drag	wet	d1958	0	239	115282	696	0	57974	0	0	0	17400	0	20950
110.7.1	drag	dry	d1280	0	0	80078	0	0	2474518	0	365845	3429	668399	0	0
110.7.1	drag	dry	d1298	8	0	114874	34	0	1086558	172143	464924	5129	283960	0	0
110.7.1	drag	dry	d1323	1	0	71086	0	2298	736083	202271	777067	10450	296127	0	11068
110.7.1	drag	wet	d1346	0	0	88409	0	1935	254862	195497	457550	0	59681	0	0
110.7.1	drag	wet	d1368	0	0	77759	0	11322	325412	756886	2038868	29978	161194	0	0
110.7.1	drag	wet	d1388	0	0	87639	0	2322	25364	762162	1997056	42271	84291	0	0
110.8.1	drag	dry	d1413	0	0	52053	0	0	24332	0	42000	2353	2424	0	0
110.8.1	drag	dry	d1430	0	0	47770	0	0	40413	0	17062	0	5197	0	0
110.8.1	drag	dry	d1450	0	0	35087	0	0	0	0	0	0	0	0	0
110.8.1	drag	wet	d1468	0	0	36312	0	0	0	0	0	0	0	0	0
110.8.1	drag	wet	d1488	0	0	22148	0	0	43766	0	0	0	12858	0	0
110.8.1	drag	wet	d1509	0	0	106176	0	0	81552	0	0	0	15607	0	0
110.9.1	drag	dry	d1725	0	0	75649	0	0	135416	0	54153	0	24213	0	0
110.9.1	drag	dry	d1747	0	0	37250	0	0	137791	0	0	0	11225	0	0
110.9.1	drag	dry	d1764	0	0	31107	52	0	69017	25883	33999	0	10610	0	0
110.9.1	drag	wet	d1780	0	121	21907	61	0	86930	25385	0	34629	5531	4913	0
110.9.1	drag	wet	d1798	0	0	53381	0	0	39241	0	0	0	13600	0	0
110.9.1	drag	wet	d1814	0	0	36713	0	0	101949	0	41138	0	21108	0	0
110.9.2	drag	dry	d1532	126	122	18569	0	3956	471883	422358	875503	0	170797	0	0
110.9.2	drag	dry	d1563	0	0	129008	0	0	338745	71727	488347	2029	67421	0	0
110.9.2	drag	dry	d1600	0	0	109028	0	0	339312	123250	644913	1905	97453	0	0
110.9.2	drag	wet	d1631	47	0	159346	0	17565	1231489	1092405	2521171	0	318993	0	0
110.9.2	drag	wet	d1664	0	0	145622	0	28404	583207	1808232	2896262	9058	345897	0	0
110.9.2	drag	wet	d1697	0	0	172117	0	10325	284132	1194127	3138044	1614	409613	0	0

Soil Sample no.	Soil Transfer Method	Soil moisture content	Digital Photo no.	Munsell colour range (Area of each colour in pixels)												
				10YR												
				2/1	2/2	3/1	3/2	4/2	4/3	5/2	5/3	5/4	6/3	6/4	6/6	7/2
110.5.1	drag	dry	d0923	0	0	0	0	0	8594	0	4871	1627	39965	0	0	17304
110.5.1	drag	dry	d0940	0	0	0	0	0	0	3841	0	0	4815	0	0	9821
110.5.1	drag	dry	d0951	0	0	0	0	0	4831	0	9009	1035	39216	0	0	48534
110.5.1	drag	wet	d0960	0	0	0	0	0	0	0	4497	2791	63258	0	0	9512
110.5.1	drag	wet	d0975	0	0	0	0	0	0	7999	18106	5807	84337	16872	0	123635
110.5.1	drag	wet	d0988	0	0	0	0	0	0	0	12735	1584	74571	812	0	108605
110.6.1	drag	dry	d1146	0	0	0	0	0	0	0	3062	0	4835	0	0	0
110.6.1	drag	dry	d1172	0	0	0	0	0	3260	0	0	0	17930	0	0	5596
110.6.1	drag	dry	d1193	0	0	0	0	0	0	0	0	0	8737	0	0	4658
110.6.1	drag	wet	d1220	0	0	0	0	3188	1783	0	32993	8313	113309	6462	0	122005
110.6.1	drag	wet	d1241	0	0	0	0	0	0	0	17281	10333	128533	898	0	98707
110.6.1	drag	wet	d1260	0	0	0	0	0	0	0	9668	4356	21074	0	0	36990
110.6.2	drag	dry	d1840	0	0	0	0	0	0	0	6549	0	26724	0	0	24653
110.6.2	drag	dry	d1865	0	0	0	0	0	0	0	0	0	33694	0	0	14488
110.6.2	drag	dry	d1889	0	0	0	0	0	0	0	0	0	0	0	0	21427
110.6.2	drag	wet	d1912	0	0	0	0	0	0	0	0	0	23072	3213	0	36802
110.6.2	drag	wet	d1934	0	0	0	0	0	0	0	0	0	8815	0	0	35590
110.6.2	drag	wet	d1958	0	0	0	0	0	0	3641	0	0	25274	0	0	14064
110.7.1	drag	dry	d1280	0	0	0	0	215155	29892	61336	17698	1681	170577	0	0	47076
110.7.1	drag	dry	d1298	0	0	0	0	150695	40825	33776	38327	3750	177262	1656	0	106122
110.7.1	drag	dry	d1323	0	0	0	0	121451	55321	65694	21543	7876	233031	8183	0	163613
110.7.1	drag	wet	d1346	0	0	0	0	23446	18575	13111	6109	604	54799	0	0	20694
110.7.1	drag	wet	d1368	0	0	0	0	57862	130192	29053	104840	6854	370562	0	0	204645
110.7.1	drag	wet	d1388	0	0	0	0	7009	140584	8072	145026	26655	527096	3811	0	579963
110.8.1	drag	dry	d1413	0	0	0	0	3166	4573	0	0	0	9106	0	0	0
110.8.1	drag	dry	d1430	0	0	0	0	0	0	0	0	0	18860	0	0	20871
110.8.1	drag	dry	d1450	0	0	0	0	0	0	0	0	0	0	0	0	6083
110.8.1	drag	wet	d1468	0	0	0	0	0	0	0	0	0	0	0	0	6490
110.8.1	drag	wet	d1488	0	0	0	0	2787	0	7855	0	827	5028	0	0	0
110.8.1	drag	wet	d1509	0	0	0	0	0	0	3367	3310	0	10969	0	0	15361
110.9.1	drag	dry	d1725	0	0	0	0	0	1576	14968	7714	0	54195	0	0	49054
110.9.1	drag	dry	d1747	0	0	0	0	5669	5100	0	2820	1593	39016	0	0	32206
110.9.1	drag	dry	d1764	0	0	0	0	0	1398	3742	3994	1070	18416	4176	0	25480
110.9.1	drag	wet	d1780	0	0	0	0	3995	1353	3538	0	0	25784	0	0	13954
110.9.1	drag	wet	d1798	0	0	0	0	4235	1425	4162	0	0	65105	0	0	111153
110.9.1	drag	wet	d1814	0	0	0	0	5365	4042	10235	5478	0	47233	0	0	38878
110.9.2	drag	dry	d1532	0	0	0	0	118188	26494	51720	3523	0	30505	0	0	18937
110.9.2	drag	dry	d1563	0	0	0	0	35341	15433	50263	6043	575	78304	0	0	29579
110.9.2	drag	dry	d1600	0	0	0	0	40944	10172	67638	25990	2056	194771	0	0	117478
110.9.2	drag	wet	d1631	0	0	0	0	251492	117341	110215	46498	2582	373810	0	0	119050
110.9.2	drag	wet	d1664	0	0	0	0	173640	217797	48211	65892	14799	406602	0	0	204336
110.9.2	drag	wet	d1697	0	0	0	12385	119736	286754	39344	193941	21102	545406	0	0	391694

Are there any plans to further the study by looking at other soil types?

I have one paper soon to be published and another two papers submitted for publication. These final two papers broaden my research to include a larger variety of soil types from across Tasmania.

I currently do not have funding to continue my research in this new field of forensic soil analysis.

Do you feel that this study will extend well beyond this case in being able to help solve other crimes?

My research has shown trace soil patterns can be used to interpret the method of soil transfer to clothing and therefore the circumstances befalling a victim during or after an attack. It therefore has the potential to provide useful investigative evidence in crimes where soil has been transferred to items of clothing.

By treating trace soil patterns as a distinct form of forensic soil evidence, and preserving these patterns via digital photography at the crime scene before a body is moved or clothing

removed, trace soil analysis could provide police with critical physical evidence of the circumstances befalling the victim, to be used as evidence during a criminal trial.
The original unsolved homicide that instigated this research was originally trialled in the Supreme Court of Western Australia. Under Western Australian law, there is no 'double jeopardy'. Therefore, murder suspects could be tried again for the same crime if new evidence came to light.

Anything else you would like to share?

I am hoping that forensic soil scientists and computer software developers will team up to design purpose-built image processing software for analyzing trace soil evidence on clothing fabric, shoes, car tires, carpet, furniture and other items of evidence. A fully automated system that doesn't require the operator to be a soil expert would be of most benefit to police and general forensic scientists.

Most police forensic laboratories do not test all clothing items associated with a major crime for soil evidence. This may be due to a massive backlog of soil evidence from other cases awaiting analysis, a lack of funding, limited access to XRD machines or lack of technical expertise. If image processing software was developed to provide police with a cheap, quick, accurate and accessible method of 'in-house' analysis of soil evidence on clothing, trace soil analysis may become as routine as DNA testing and fingerprint analysis. This image processing method might also be used to uncover new forensic soil evidence in cold case crimes for police to investigate.

References

Fitzpatrick R.W., and Raven M.D. (2016). Guidelines for Conducting Criminal and Environmental Soil Forensic Investigations (Version 10.1). Report CAFSS_076, Centre for Australian Forensic Soil Science, 46pp.
http://www.adelaide.edu.au/directory/robert.fitzpatrick?dsn=directory.file;field=data;id=35757;m=view (accessed 11 February, 2016).
Fitzpatrick R.W. and Raven MD (2012) How Pedology and mineralogy helped solve a double murder case: Using forensics to inspire future generations of soil scientists. Soil Horizons. 53 (5). doi:10.2136/sh12-05-0016.

About the Authors

Kathleen Murray is a forensic soil scientist working to develop methods to assist police in solving criminal cases.

Professor Rob Fitzpatrick has focused on the interface of soil science (pedology), regolith science, mineralogy, biogeochemistry, forensic science, mineral exploration and climate change as applied to: landscape processes, advanced techniques to characterize, map, monitor and manage soil-regolith systems, criminal and environmental forensic techniques for soils and regolith, He has over 40 years' experience in leading major multi-disciplinary research projects and has conducted over 500 specialized soil-regolith investigations and surveys, covering a wide range of regions and climates worldwide.

Professor Hilton Kobus has over 40 years' experience in both operational and academic forensic science. He started in forensic science in Zimbabwe from 1968-1981 and moved to the Australian National University in 1981 as a research fellow funded by the Australian Federal Police investigating the science of fingerprint detection. He joined the Forensic Science South Australia (FSSA) in 1984 as Chief Scientist and became Director of FSSA from 1997-2007. In this role managed an organisation of 120 people that included pathologists, scientists, technicians and administrative personnel that provided broad ranging forensic science services to the South Australian Justice system. This period saw a significant expansion in the forensic science capability to South Australia with a major development being the establishment of a DNA database in support of criminal investigation.

Associate Professor Ron Berry has 30 years' experience studying the geology of Tasmania. He is an Associate Professor in Geology at the University of Tasmania. Ron's later research has focused on the emerging field of geometallurgy, using mineralogy and microtexture to predict processing performance in grinding and flotation. He has developed a protocol for automated mineral mapping using optical microscopy and mapping protocols for a laser Raman microscope.

Ralph Bottrill is a geologist, mineralogist, petrologist and mineral collector (from childhood). He works for Mineral Resources Tasmania, running the mineralogy/petrology labs and rock collection; studying various Tasmanian mineral deposits, rocks and minerals; analyzing and describing samples. He is an associate curator for minerals with both the Tasmanian Museum and the Queen Victoria Museum. He is currently President of the Mineralogical Society of Tasmania, and a member of the Mineralogical Society of Great Britain, the Mineralogical Association of Canada, the Society for Mineral Museum Professionals and the Specialist group for Geochemistry, Mineralogy and Petrology (Geological Society of Australia), He is an associate editor for the Australian Journal of Mineralogy and a registered valuer of minerals and meteorites under the Australian Cultural Heritage Act.

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Posted by Albert Munsell.