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# Examining the transfer of soils to clothing materials: implications for forensic investigations

Frances A Procter[1]; Graeme T Swindles[1,2], Natasha L M Barlow[3]

1 School of Geography, University of Leeds, UK

2 Ottawa-Carleton Geoscience Centre and Department of Earth Sciences, Carleton University, Ottawa, Ontario, Canada

3 School of Earth and Environment, University of Leeds, UK

*Corresponding author: gy14fap@leeds.ac.uk

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**Abstract**

Soil forensics has proven instrumental in assisting criminal investigation, and there is an increasing demand for experimental studies on such trace evidence. Here we present the first detailed study on the influence of clothing materials in soil transfer. We adopt an experimental approach to test the transfer of five common UK soils to five different clothing materials. Our experiment is designed to represent victim or perpetrator contact with soil at the scene of a crime. We highlight the complex relationship between soil transfer and clothing material type. Whilst over half of our soils tested displayed differential transfer to different clothing materials, soil moisture content and soil type were found to have a greater influence on the transfer of soils overall. Soil transfer is typically more effective across all material types when soils are wet and saturated. However, we find the relationship between soil transfer and material type to be more complex when soils are dry, with a significant bias in soil transfer to fleece material, which we attribute to static attraction. Encouragingly, for the analysis of forensic soils recovered from clothing artefacts, each of the transfer experiments we conducted led to soil transfer to every tested material. We suggest that future empirical studies now focus on the persistence of soils over time to clothing materials after transfer has occurred, and the transfer and persistence of soil palynomorphs present within soils.

## 1.0 Introduction

Forensic soil analysis has long been implemented in multiple high profile criminal justice cases, from murders such as the Soham Murders, UK, to international justice cases such as the Bosnian genocide (Ruffell, 2006; Kukes, 2015). In forensic scenarios, soils are frequently recovered from artefacts and clothing that may be used to link or eliminate potential scenes of crime from suspects and victims (Petraco et al., 2008; Swindles and Ruffell, 2009; Fitzpatrick and Raven, 2012; Fitzpatrick et al., 2014; Singletary and Hanna, 2018). The assumption of being able to utilise such evidence is underpinned by Locard's Exchange Principle (1930) which states that wherever there is contact between two objects, a 'mutual exchange of matter' will occur. In the specific case of clothing, trace soil evidence including pollen and mineralogical profiles have been recovered from clothing and shoes, even after cleaning in a washing machine and dry cleaning (Bull et al., 2006; Fitzpatrick et al., 2014). This highlights the importance of understanding soil as a forensic trace evidence, and its relationship with evidentiary materials such as clothing.

Soils recovered from clothing materials are useful to forensic investigations as they can be used in both investigative intelligence, for instance in narrowing search areas for crime scenes and/or suspects (Pringle et al., 2012), and also in court evidence to provide potential exclusionary evidence. It is the heterogeneity of soils which makes them so useful to criminal investigations; each soil is created from and characterised by unique geological and biological origins. Therefore, soils are extremely useful trace evidence, and can be subjected to multiple analyses of both the organic and inorganic fractions. From the inorganic soil fraction, colour (Junger, 1996; Sugita and Marumo, 1996), particle size distribution (Dudley, 1976; Blott et al., 2004; Pye and Blott., 2004), mineral composition (Graves, 1979; Ruffell and Wiltshire, 2004; Murray, 2004; Ruffell and McKinley, 2005; Petraco et al., 2008), elemental composition analysis (Petraco et al., 2008; Raut, 2012; Singletary and Hanna, 2018), particle size distribution (Sugita and Marumo, 2001) and scanning electron microscopy (Cengiz et al., 2004; Ruffell and McKinley, 2008; Pirrie, 2018) can all be used to differentiate between forensic soils. In terms of the organic fraction, soil organic matter (Melo et al., 2018), mycology (Wiltshire et al., 2014) and palynology (Mildenhall et al., 2006; Wiltshire et al., 2014; Wiltshire, 2016), can prove to be powerful tools in forensic science as no two locations' palynological profiles have yet been found to be precisely identical (Wiltshire et al., 2014).

Research suggests the characteristics of the ideal trace evidence to be: (1) that traces can be almost invisible; (2) traces are highly individualistic; (3) there is a high probability of transfer and retention; (4) traces can be quickly collected, separated and concentrated; (5) smallest traces are easily characterised; and (6) there is capacity for a computerised database from which to search (Aardahl, 2003; Fitzpatrick et al., 2009); all of which may suitably be applied to describe forensic soils. Whilst the key characteristic of 'a high probability of transfer and retention' is relatively well supported in published case material, it is yet to be empirically tested for soil on clothing materials. There is great abundance of excelling forensic soil science being applied to true-crime cases documented in the literature (Petraco et al., 2008; Swindles and Ruffell., 2009; Ruffell and Schneck, 2017), however the need for further empirical research continues to prevail.

In a 2017 report by the UK Forensic Science Regulator, it is explicitly recommended that forensic science research now focusses on 'structured studies on the transfer and persistence of trace evidence and the significant factors affecting such transfer'. While there has been much recent interest in transfer and persistence studies of trace evidence (Morgan et al., 2014; Scott et al., 2014; Stoney et al., 2016; Levin et al., 2017; Webb et al., 2018; Gassner et al., 2019; Maitre et al., 2019; Scott et al., 2019;), there have been no studies focussing on how different clothing materials affect the transfer of soil. In a recent attempt to understand soil transfer patterns onto nylon-elastane bras, Murray et al., (2016; 2017) found mineralogy, clay content and moisture content especially to influence soil transfer. This research suggests that multiple factors affect the transfer of soil, however the influence of clothing materials is yet to be tested. As such, we present the first study towards understanding the transfer of soils to common clothing materials and the factors which may affect such transfer.

### 1.1 Aims

In this paper, we aim to identify how soils transfer to different common clothing materials, by conducting an extensive laboratory-based soil transfer experiment. Specifically, we aim to quantify the amount of soil transferred to five different clothing materials, exposed to the same conditions, and to determine the relative influence of clothing material type on soil transfer under controlled laboratory conditions.

### 1.2 Hypotheses

Multiple studies have been conducted on the transfer and persistence of artificial trace evidence, such as glass fragments, textile fibres, gunshot residue and fluorescent powder to clothing materials, which suggest that clothing material type does influence the transfer and persistence of trace matter (Hicks et al., 1996; Allen et al., 1998; Bull et al., 2006). As such we test the following hypotheses: 1) clothing material will influence the quantity of soil transferred; and 2) open-weaved clothing materials (cotton and denim) and fibrous material (fleece) will enable a greater amount of soil transfer than smoother and closed-weave materials (nylon and leatherette).

## 2.0 Methods and Materials

We conducted a laboratory-based soil transfer experiment with 225 individual runs (including replicates), to determine the extent to which five UK soils transferred to five commonly worn clothing materials. We constructed a scenario designed to imitate brief contact of a person's clothing with soil.

### 2.1 Soil samples

Five different soil types were collected within a 30 km radius across West Yorkshire, UK (Figures 1 and 2; Table 1). All soils are from the same underlying bedrock geology, which are sandstones of the Carboniferous Millstone Grit Group. A woodland soil was collected from a semi-rural woodland in Todmorden; and a parkland soil was collected from the nearby semi-rural public park. A streamside alluvial soil was collected from an accessible river bank behind a suburban recreation park, Todmorden. An organic-rich peaty soil was collected from Ilkley Moor, an upland moorland environment. A glacial till-derived soil was also collected from Ilkley Moor, accessed via a river cutting. The protocol we used for soil sample collection is outlined in Figure 3. Table 1 presents characteristics of each soil including basic descriptions, colour, pH, organic content, and particle size distribution.

### 2.2 Clothing materials

Five commonly worn clothing materials: (1) cotton; (2) denim; (3) fleece; (4) nylon; (5) and leatherette (faux leather PVC), were selected and purchased new from a textiles shop (Table 2). Materials were used new and unwashed. To simulate a clothed body, materials were cut into swatches approximately 400 x 400 mm to wrap around a custom 2 kg weight (Figure 4). Cotton, denim, fleece and nylon swatches were secured to the weight with elastic bands, and the less flexible leatherette was carefully secured with masking tape, to enable easy removal of the material from the weight after the transfer experiment with minimal impact on the soil retained.

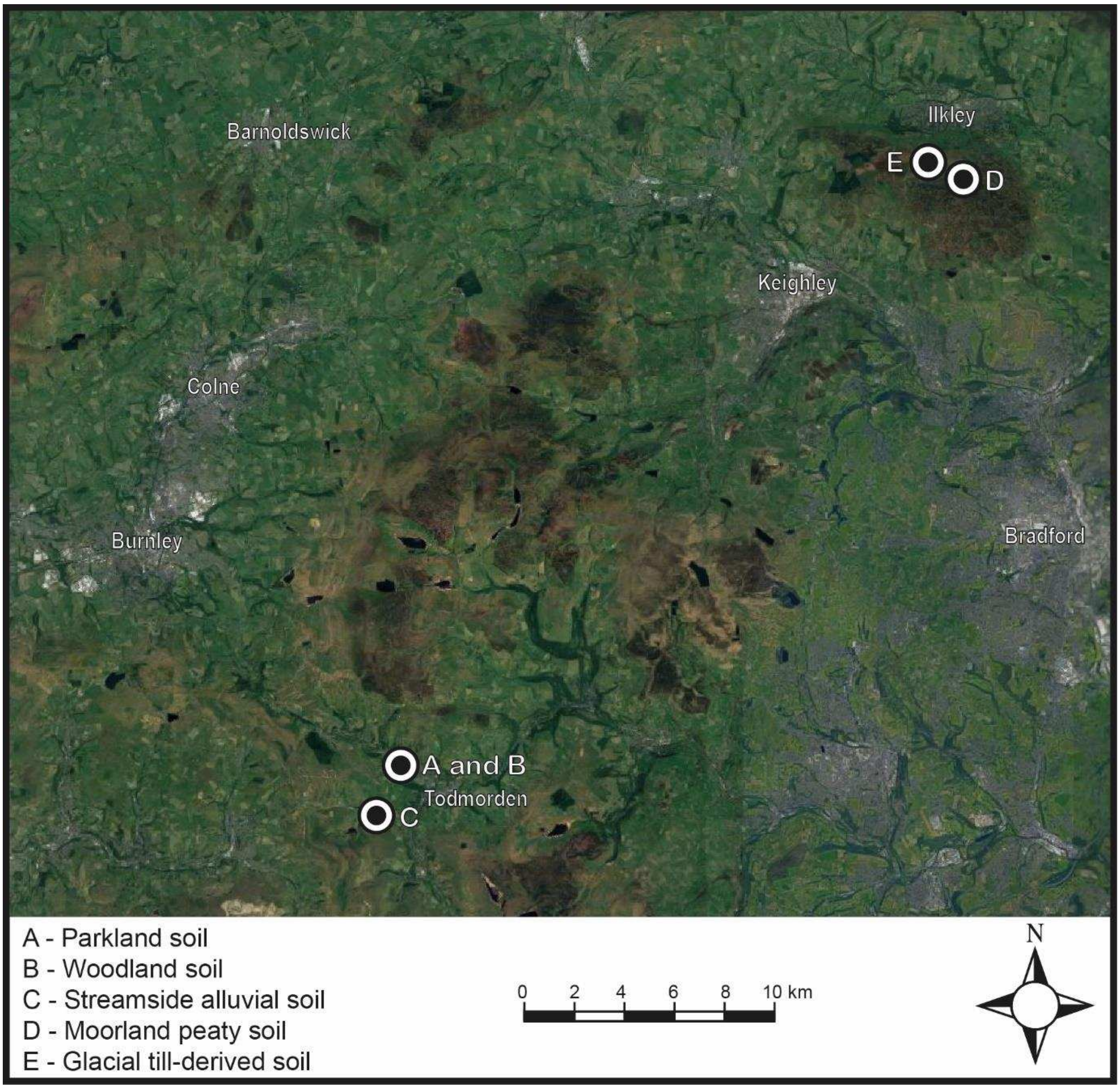



Figure 1: Location map of soil sample collection sites: A) semi-rural public parkland soil: 53° 71’ 77. 65”N, 2°10’ 60.327”W; B) woodland soil: 53° 71’ 59.68”N, 2° 10’ 60.282”W; C) streamside alluvial soil: 53° 70’ 51.71”N, 2° 11’ 81.197; D) Ilkley Moor, moorland peaty soil: 53° 91’ 44.93”N, 1° 80’ 66.187W; E) Ilkley Moor, glacial till-derived soil: 53° 91’ 62.95”N, 1° 80’ 96.553”W. Image from Google Maps 2019 (viewed 1 July 2019).


Figure 2: Site photographs of soil sample collection: A) parkland soil; B) woodland soil; C) streamside alluvial soil; D) moorland peaty soil; E) glacial till-derived soil.

| Soil type | Colour | pH | Organic content | Particle size distribution | Description |
|---|---|---|---|---|---|
| **Parkland soil** | 2.5Y 4/2<br>Dark greyish brown | 6.06 | 9% | Coarse sand: 17%<br>Medium sand: 68%<br>Fine sand: 11%<br>Silt and clay: 4% | Sandy loam. ~10% mottling of sand grains. Anthropogenic inclusions of brick, pottery and plastics <1%. Modified anthroposol. |
| **Woodland soil** | 5Y 2.5/2<br>Black | 5.47 | 33% | Coarse sand: 62%<br>Medium sand: 26%<br>Fine sand: 9%<br>Silt and clay: 3% | Sandy loam. ~5% large organic inclusions, twigs and seeds |
| **Moorland peaty soil** | 5YR 2.5/1<br>Black | 3.52 | 50% | Coarse sand: 53%<br>Medium sand: 31%<br>Fine sand: 11%<br>Silt and clay: 5% | Peaty soil. High organic content |
| **Streamside alluvial soil** | 10YR 4/4<br>Dark yellowish brown | 4.80 | 9% | Coarse sand: 26%<br>Medium sand: 56%<br>Fine sand: 13%<br>Silt and clay: 5% | Sandy sediment |
| **Glacial till-derived soil** | 2.5Y 5/6<br>Light olive brown | 3.61 | 4% | Coarse sand: 46%<br>Medium sand: 38%<br>Fine sand: 9%<br>Silt and clay: 7% | Very clay rich till, with a sticky texture. Clast inclusions ~20% |

Table 1: Characteristics of the five soil types used in this study including: soil colour; pH; organic matter; and particle size distribution of the <2 mm fraction where: coarse sand (2 mm-500 µm); medium sand (500 µm-150 µm); fine sand (150-64 µm); and silt and clay (≤63 µm).

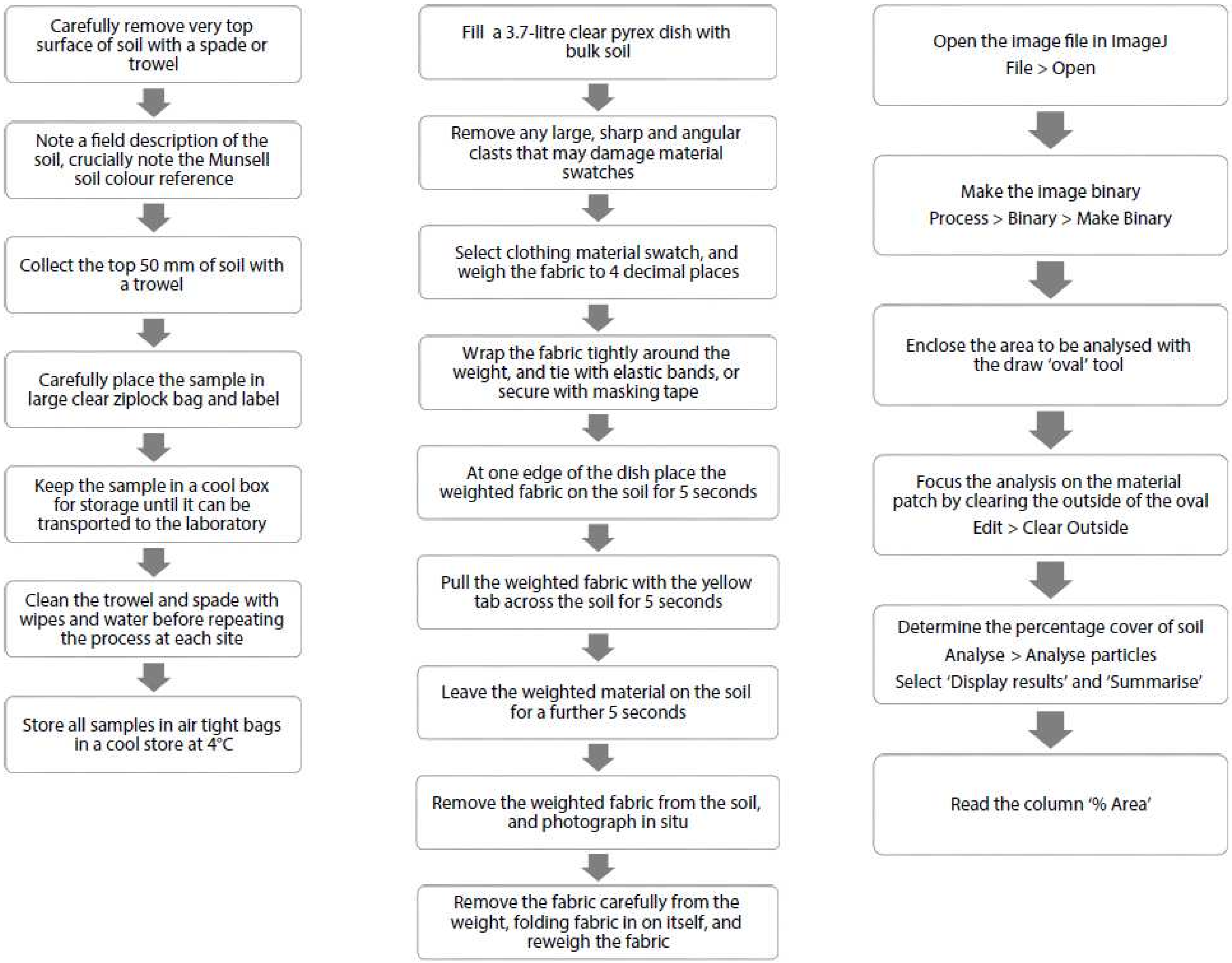
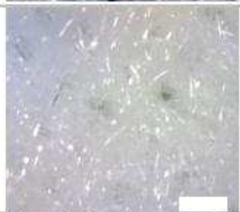
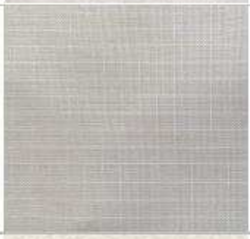
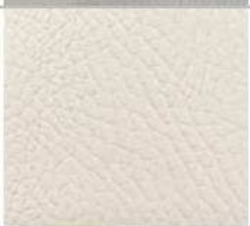



Figure 3: The protocol used in this soil transfer experiment, including soil collection, laboratory soil transfer, and post-transfer analysis in imageJ.

Table 2: Photographs, photomicrographs (scale bar is 500 µm) and properties of the five clothing materials used in this study.

| | Photograph | Photomicrograph | Material Composition | Fibre Type | Characteristics |
|---|---|---|---|---|---|
| Cotton |  |  | 100% cotton | Natural | Coarse open weave and fibrous |
| Denim |  |  | 100% cotton | Natural | Coarse open weave and fibrous |
| Fleece |  |  | 100% acrylic polyester | Synthetic | Artificial fibrous texture |
| Nylon |  |  | 100% nylon | Synthetic | Closed weave, square textured pattern |
| Leatherette |  |  | 100% PVC | Synthetic | Closed weave, smooth texture with some mottled pattern |

### 2.3 Soil transfer experiments

To create a controlled and repeatable experiment, we implemented the successful and field-verified laboratory set up design of Murray et al., (2016; 2017) with minor modifications (Figures 3 and 4). The different fabric swatches were wrapped around a custom 2 kg weight providing a 116.89 $cm^2$ area of contact (Figure 4), and were dragged over the soils for 5 seconds. The simulated soil surface was a 3.7 L Perspex tray filled with bulk soil, with sharp clasts, twigs >20 mm, and pebbles >20 mm removed to prevent damage to the clothing materials. The soil was levelled but not compacted. The cladded weight was placed on the soil and dragged from one side of the soil surface to the other, for a duration of five seconds, and a total contact duration of 15 seconds (Figure 3). After each soil transfer experiment the clothing material was photographed whilst attached to the weight. Photographs were taken on a Canon PowerShot SX40 14 megapixel digital camera, of similar specification typically available to a forensic investigator at the scene of a crime. Photomicrographs were taken using an APEX MiniGrab USB microscope camera and Brunel light microscope, to enable a closer look at the fabric-soil interactions. Fabric swatches were then removed from the 2 kg weight and weighed to 4 decimal places. Elastic bands were cut to remove the materials and to reduce disturbance of any transferred soil. Each soil transfer experiment was run in triplicate.

### 2.4 Soil moisture

It is suggested that soil moisture has a significant influence on soil transfer (Murray et al., 2016; 2017), therefore we conducted our soil transfer experiments at three different moisture contents: ‘dry’, ‘wet’, and ‘saturated’. Each experiment was first conducted with wet soil, akin to field moisture. Wet soils varied in moisture content between

25.4% and 57.7%, however were all visibly wet, and wet to the touch. Deionised water was then added to the soils until the point of saturation and the experiment repeated. Due to the nature of the different soils, the wetness and saturation point was different for each soil (Table 3). Throughout wet and saturated transfer experiments, a mist spray of deionised water was used to counteract evaporation and maintain constant moisture content. Soils were then air dried before conducting the experiment 'dry'. When altering the moisture content of the soils, a Delta-T theta soil-moisture probe was used to estimate soil moisture content to allow samples to be as comparable as possible. Absolute moisture contents were determined by oven drying subsamples at 105℃ (Table 3).

Table 3: Soil moisture content (%) for each soil in the transfer experiment.

| | Dry | Wet | Saturated |
|---|---|---|---|
| Parkland soil | 23.0 | 31.3 | 34.0 |
| Woodland soil | 40.8 | 57.7 | 64.0 |
| Streamside alluvial soil | 1.9 | 21.7 | 26.4 |
| Moorland peaty soil | 24.5 | 55.3 | 63.1 |
| Glacial till-derived soil | 11.4 | 25.4 | 54.1 |

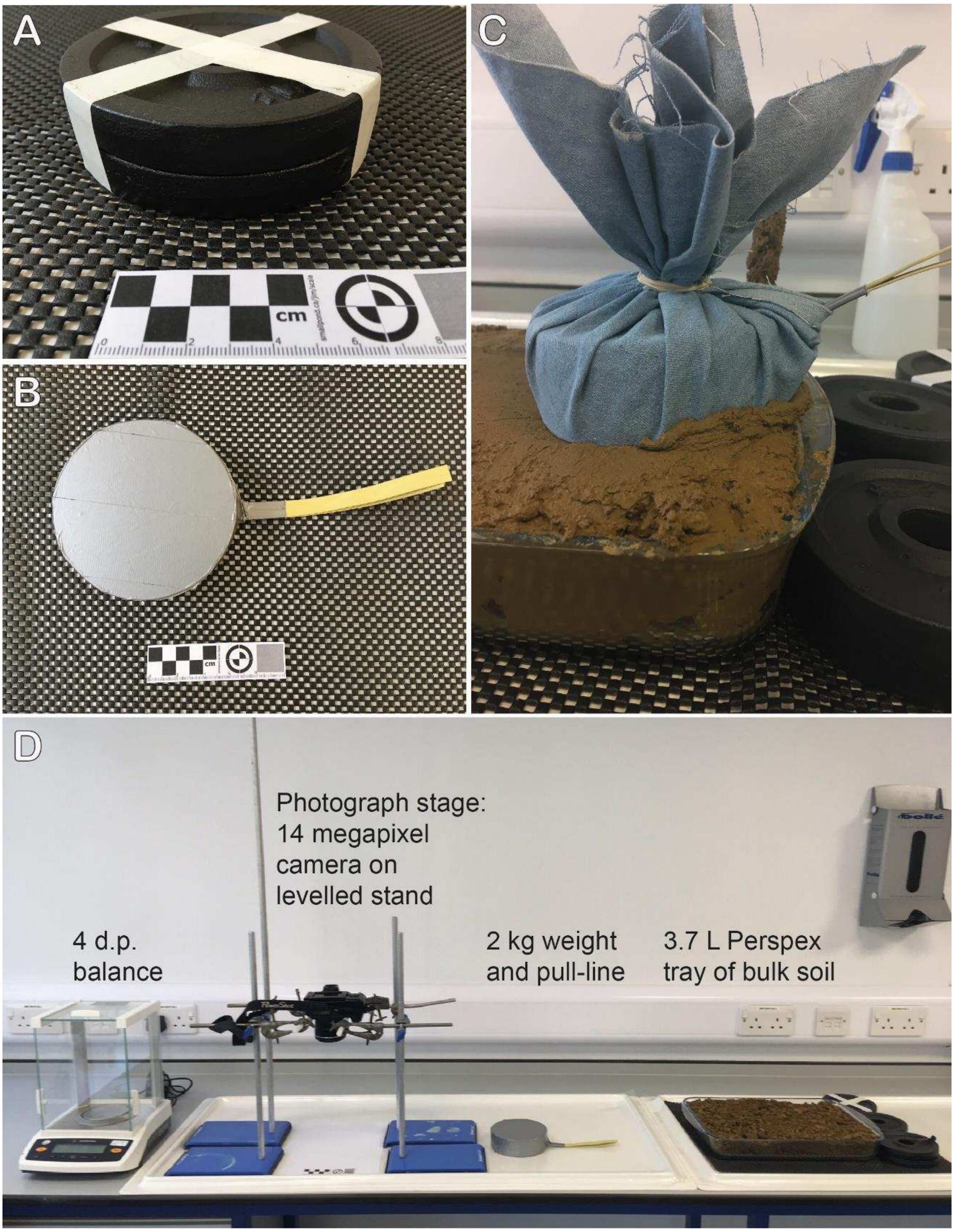



Figure 4: Experiment laboratory set up: A) 2 x 1 kg weights secured together; B) 2 kg weight and strong plastic pull-line; C) cladded weight in denim secured with an elastic band, being dragged across the glacial till-derived soil surface; D) laboratory workspace showing the soil surface set up, in-situ photography stand, and weighing balance.

### 2.5 Post-transfer analysis

Image analysis software imageJ (1.39u – documentation and downloads at website http://rsbweb.nih.gov/ij/, National Institutes of Health, Bethesda, Maryland, USA), was used to quantitatively determine the amount of soil transferred to each material by calculating the total percentage cover of soil on the fabric (Figure 3). Adjusting the image threshold highlighted the soil from the background clothing material (Figure 5). Pixels containing transferred soil were counted, enabling us to calculate the total area of soil-stained material, as a percentage of the total area of material in contact with the soil. This provided us with a comparable set of soil transfer values for each clothing material. The amount of soil transferred was also recorded by weighing the clothing material swatches pre- and post-soil transfer. Transfer weight data was corroborated against the image analysis to further examine the nature of soil transfer to the different clothing materials. Statistical analyses were conducted on the more robust image analysis data to quantify any differences.

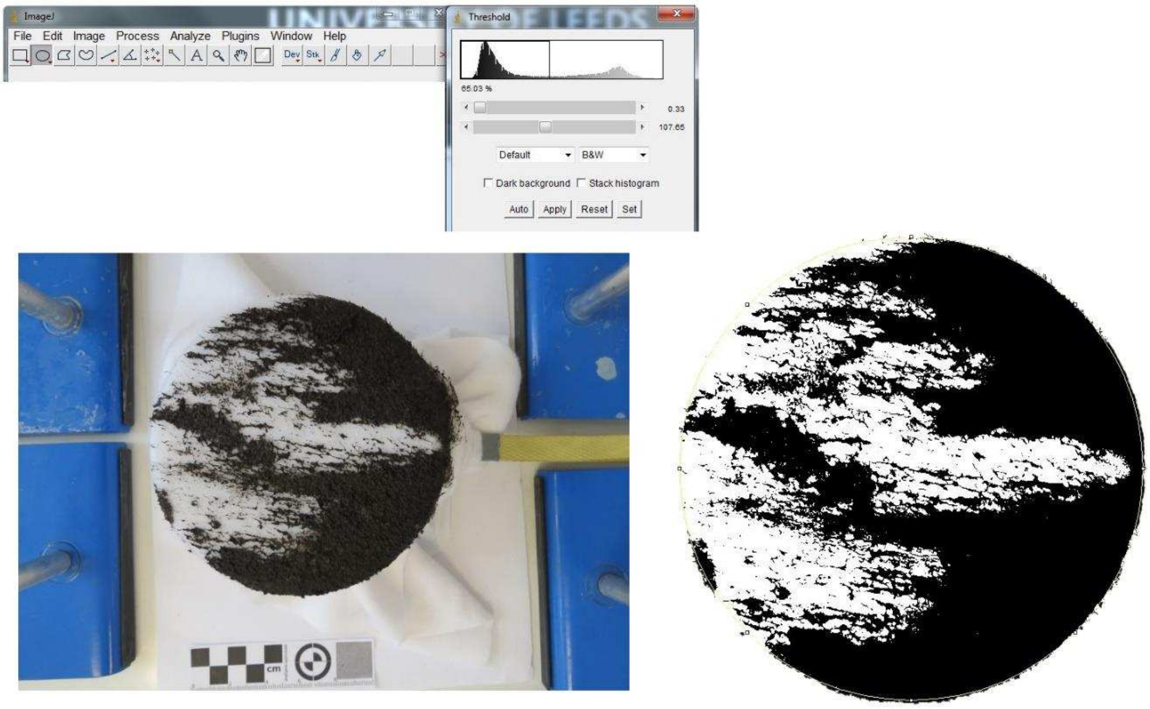



Figure 5: Adjusted image threshold in imageJ highlighting only the soil on the photograph, and area of interest highlighted using the oval tool, next to the original photograph.

## 3.0 Results

The results of our soil transfer experiments are presented in Figure 6. It is clear there is great variation in soil transfer, with a greater quantity of soil transfer with increasing soil moisture content. As such, to enable a better insight into the relative influence of clothing materials specifically on soil transfer, we make our comparisons within the three moisture content subsets. Soil transfer measured in percentage area of soil coverage and weight of soil transfer are available in the supplementary information.

ANOVA tests for differences conducted between the mean soil transferred (area coverage) to the different clothing materials identify significant differences for nine of the fifteen soils tested (Supplementary Table 1). Both cotton and fleece materials consistently prevail in having the greatest mean soil transfer. By fitting linear regression models, we are able to further statistically explore the relationships between soil transfer to the different materials and the relative influence of the factors affecting this transfer. We find that soil moisture has the greatest influence on soil transfer to clothing materials. The linear regression model between soil transfer and soil moisture ($R^2$=0.782, p=0.000) reflects a strong significant relationship between soil moisture content and the amount of soil transferred. Our linear regression model between soil transfer, soil moisture, soil type, and clothing material type, however ($R^2$=0.809, p=0.000) highlights that soil type and fabric type do contribute to the degree of soil transfer. The extent to which clothing material type and soil type affects soil transfer of dry, wet and saturated soils is described below

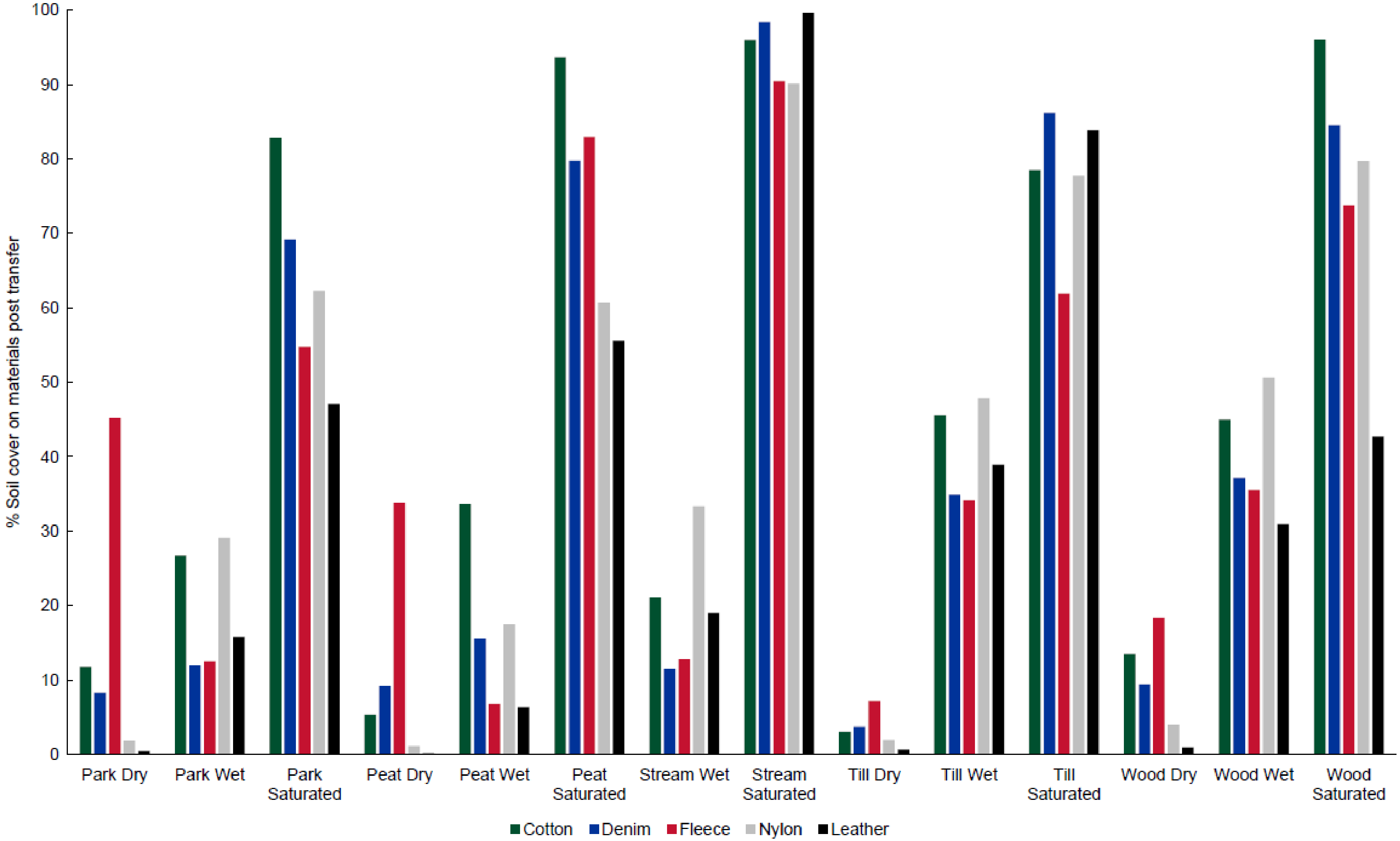



Figure 6: Average percentage area of soil coverage on each clothing material, following soil transfer. Dry streamside alluvial soil omitted.

### 3.1 Dry Soils

In our dry soils, clothing material type has a greater influence on soil transfer than soil type, with linear regression models of $R^2$= 0.515, p=0.000 and $R^2$=0.000, p=0.110 respectively. Dry soils demonstrate the greatest variability in soil transfer between clothing materials. Transfer of each of the dry soils is greater to cotton and denim (natural and open weaved fabrics), than the nylon and leather (both synthetic and closed weaved). The greatest quantity of soil transfer is however to the fleece material, with a notable increase in soil transfer of all the dry soils to this material. This significant transfer is highlighted in Figure 7. We attribute this predominantly to the static nature of the fabric. This bias in transfer to fleece material is also typically reflected in the weight data. Of the dry soil transfers weighed, only the glacial-till derived soil was not most abundant in transfer to fleece – where the clay-like material may not have been attracted statically. The driest soil sample, the dry streamside alluvial soil (only 2% moisture content) proved difficult to calculate a percentage-area coverage and so was excluded from image analysis. Due to the extremely low moisture content and lack of compaction the dry alluvial soil created a fine dust, which covered the fabrics (Figure 8). This fine dusting was assumed to be the background material colour by the image analysis software, with only larger soil clasts being detected. The weight of soil transfer here is however still most abundant to fleece, followed by the open weaved cotton and denim, and least transferred to the closed weaved nylon and leatherette. Across all of the experiments, the lowest recorded soil transfer is 3.88 mg of dry glacial till-derived soil transferred to the leatherette. Although not statistically significant, there is a notable degree of variation in soil transfer between the different dry soil types, both in area of soil coverage and weight of transfer (Supplementary information).

Figure 7: Transfer of dry woodland soil to A) cotton; and B) fleece. Scale bar is 20 mm.

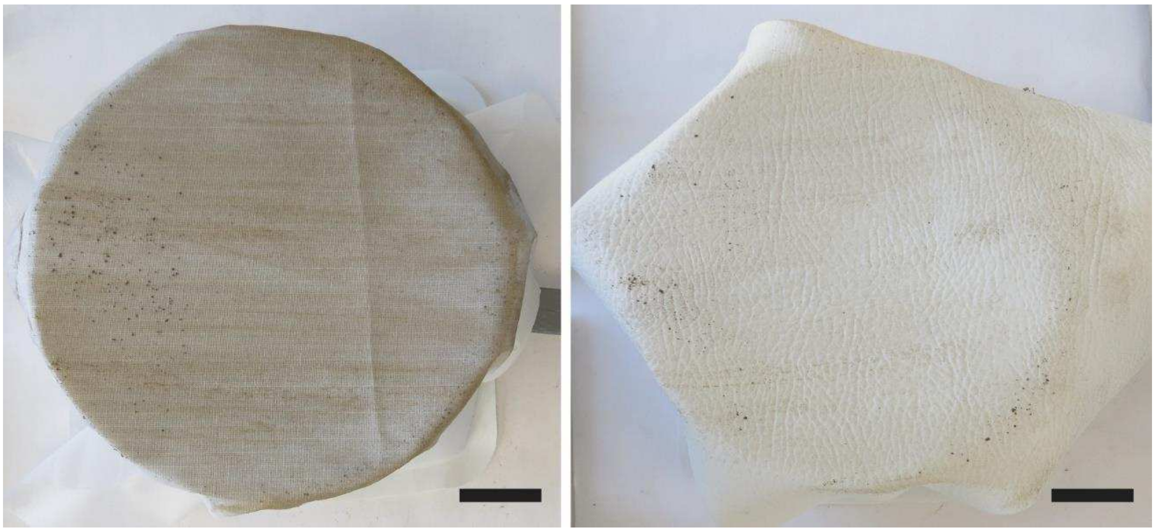


Figure 8: Transfer of dry streamside alluvial soil to A) nylon; and B) leatherette. Scale bar is 20 mm.

### 3.2 Wet Soils

Within the wet soil transfer experiments, the linear regression between soil transfer, material type and soil type shows a significant relationship $R^2$=0.654, p=0.000. Contradictory to the drier soils, soil type influences the amount of soil transfer to a greater extent than clothing material type with linear regression models of $R^2$=0.461, p=0.000 and $R^2$=0.084, p=0.003 respectively. Compared with the dry transfer experiments, transfer is more ubiquitous between the materials. Cotton consistently yields a high percentage cover of soil, with denim and fleece picking up slightly less material. The weight of soil transferred suggests denim and leather enable the greatest amount of wet soil transfer. Interestingly, both nylon and leather display relatively high amounts of soil transfer, despite having a smoother finish similar to waterproof-type materials. The fleece material consistently recovers relatively lower amounts of wet soil than the other fabrics, both in percentage cover of soil staining and in weight of transfer.

### 3.3 Saturated soils

The influence of both clothing material and soil type is less significant in more saturated soils ($R^2$=0.474, p=0.000). Again, soil type appears to have a greater relative influence on soil transfer than material type, with liner regression models $R^2$=0.259, p=0.000 and $R^2$=0.126, p=0.001 respectively. Transfer of these saturated soils again appears more ubiquitous across the different materials. Unlike the dry soils, fleece appears to pick up the least amount of saturated soils. This is however still a great amount of soil transfer with the least transfer still covering approximately 50% surface area of the material. While there appears to be great variation in the weight of soil transferred to each material, the least amount of saturated soil transfer, the saturated glacial till-derived soil transferred to fleece, still transferred a great amount of soil; weighing 1804.9 mg.

In summary, soil moisture is the dominant influence on soil transfer, however soil type and clothing material type do also contribute to the amount of soil collected onto the material. The relative influence of the clothing material decreases with increasing soil moisture, with material type being most influential on the transfer of drier soils. Transfer of soil is more ubiquitous across fabric types tested when soils are wet.

## 4.0 Discussion

### 4.1 Explanation of results

We present the first empirical study investigating the relative influence of clothing material on the transfer of soil. We hypothesised that material type will affect the amount of soil transferred in this controlled experiment, and specifically that more open weaved and fibrous materials would enable a greater amount of soil transfer. Our results show that the relationship between soil transfer and clothing material is existent, yet complicated. In wetter soils, where transfer of soils is greater, the relative influence of clothing material is reduced, and soil type becomes a relatively more influential factor. In drier soils however, clothing material can play a significant role in determining the degree of soil transfer.

The greatest amount of transfer occurred between the glacial-till derived soil and the leatherette material. In the wettest and stickiest soils, suction occurred between the soil and the materials, and larger clumps of soil particles were observed to have transferred. The highest recorded weights of soil transfer occur where large aggregates of soil particles stuck to the fabric, the volume of which is not necessarily detected in the image analysis. The lowest recorded soil transfer in the experiment:

3.88 mg of dry glacial till-derived soil, is extremely encouraging for the forensic analysis of soil recovered from clothing as it is enough to conduct many soil analysis techniques, including analysis of SOM, polarised light microscopy, and potentially XRD.

The most notable pattern observed was the significantly higher transfer of dry soils to fleece than to any other material. We attribute this to the static nature of the material, which was clearly observed in the laboratory. This static attraction enabled more dry soil particles to be lifted and adhered to the material. There is little discussion in the forensic and trace evidence literature documenting the influence of static on particulate transfer. The adhesion of ‘dirt’ to fleece by static attraction is however documented; in a patent design for new fleece with less static property (Nohara, 2007, U.S. Patent 7,213,313). This may prove to be a potential field of trace evidence research in itself.

We hypothesised that materials with a more open weave will demonstrate a greater level of soil transfer, as rougher surfaces tend to entrain larger numbers of particles. Multiple studies on the transfer of inorganic materials found a coarser, and more open weave to allow a greater degree of particulate retention (Hicks et al., 1996; Allen et al., 1998). Our photomicrographs show particles, and some larger particles entrained in these open weaved fabrics (Figure 9). Particles did transfer surprisingly well to the closed weaved nylon and leather, however both had some degree of texture which retained soil particles (Figure 9). The persistence of soils to these materials would prove an interesting study through future experimentation. Where there is significant variation within material groups, we suggest some variation could be explained by the weighted clothing material not being completely flat on the soil surface, however the soil surface was relevelled after each experiment, so variations are representative of real-life variation.

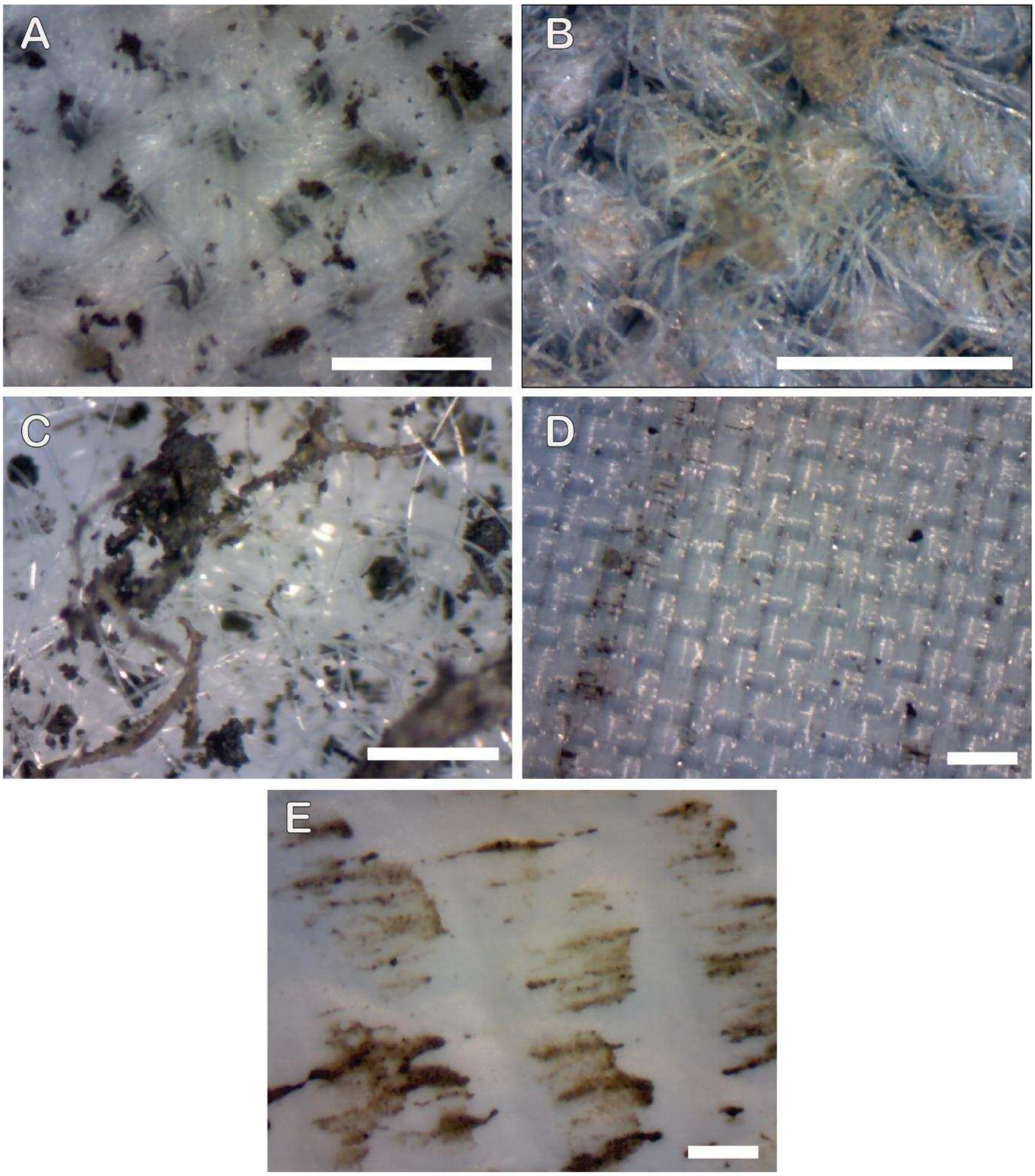



Figure 9: Photomicrographs showing closer detail soil-material interactions: A) woodland soil embedded in the weave of cotton; B) glacial till-derived soil embedded and in the fibres of denim; C) large woodland soil fragments intertwined in fleece fibres; D) parkland soil transferred along the pattern of textured nylon; E) streamside alluvial soil scraped across leatherette, adhering predominantly on the raised texture of the material. Scale bar is 1 mm long.

### 4.2 Implications of findings

We find some of our most interesting results in the transfer of dry soils. One of the crucial characteristics of trace evidence is its potential to go unnoticed by a perpetrator (Aardahl, 2003). With smaller quantities of soil transferred when dry, a suspect may be less aware of the presence of this trace evidence on their clothing, compared with the saturated soils where staining is more obvious. In the lowest yielding soil transfer experiment enough soil was still present to allow for subsequent forensic analyses, which reflects the crucial need to further understand the transfer of soil trace evidence to clothing materials. Even in the lowest yielding soil transfers, or where recovery of soil may prove difficult, the colour of the soil remained well represented on the materials, which can prove to be critical evidence alone with variations in soil colour one of the most distinguishing characteristics of trace soil evidence (Junger, 1996; Sugita and Marumo, 1996).

From our increasing understanding of the dynamics of soil transfer we may enable better interpretation of the trace evidence and can also improve approaches for the recovery of such evidence material. Understanding differential soil transfer to clothing materials may allow us to make future recommendations on the methods by which soil is recovered from evidential materials. For instance, if dry soil is found adhered to nylon or leather, where transfer is least, it may be most appropriate to use the direct tag lifting method (Pirrie, 2018) to yield evidential soil for analysis; whereas on wetter soils or materials which yielded a high degree of soil transfer, the standard washing protocol to recover the soil should prove sufficient (Ruffell and Sandiford, 2011; Pirrie, 2018).

We suggest the need to create a database for all empirical research studies on soil forensics, which may act as a reference base for casework. Here, we have 225 stock images of soil transfer, when five of the most commonly worn clothing materials come into contact with common soils across the UK. The potential of such a database is reflected in the demonstration of how image processing of crime scene photographs can provide initial and potentially crucial evidence on the colour, nature, and subsequently the provenance of soil trace evidence in a non-destructive manner (Murray et al., 2016; 2017). From such stock evidence, forensic investigators may be able to determine valuable information such as retracing potential antecedent weather conditions or ground conditions at the time of incident, narrowing a window of opportunity when such evidence may have come to be. This would also be beneficial to investigators who are not geologically trained to better understand the uniqueness of soil evidence, and to enable better consideration for the potential origins of such evidence. The creation of such database would only strengthen the criterion of soils as an ideal trace evidence (Aardahl, 2003).

This research may also have implications for biosecurity research. A great amount of research is currently focussing on the control of invasive species, the minimum amount of trace soil and plant material that can contribute to invasive species spreading, and best practice when working in the field. Our findings may prove useful when considering the most appropriate field attire when working on and around invasive species.

### 4.3 Limitations

Whilst the imageJ software was in the most part successful in independently determining the contrast between soil and the background fabric, in multiple instances with the denim swatches in particularly the image threshold needed to be adjusted manually, with the user determining when the software had picked up all of the transferred soil and excluded background noise. Whilst this may account for a slight margin-of-error, due diligence was taken by adjusting the threshold side-by-side with the original transfer photographs to allow the best possible estimation of soil transferred.

We recognise a potential limitation to this study being the replication of field activity in the laboratory, with not all natural factors being successfully replicated, for instance soil compaction. This laboratory study is however designed based on a field-verified method (Murray et al., 2016; 2017), and did also allow for better control of other factors, such as soil moisture content, levelling, and better cross-contamination control. This experiment could be repeated in the field, with the provision of high precision field-portable scales and contamination measures in place.

### 4.4 Future work and recommendations

The geographical scope of this study has the potential to be extended considerably. Whilst chosen to be representative of common UK soil types, our five soils tested do not represent all UK soils, and it is the heterogeneity of soils which makes them so useful to forensic investigations. We reinforce the suggestion that a database of all studies be compiled, to further enhance our understanding of how this unique trace evidence behaves, and to build a better picture of how soil evidence may be useful in future forensic investigation.

We have quantified the amount of soil transferred to multiple common clothing materials in a forensic setting, however there is suggestion that a rapid decay rate of transference can quickly obliterate valuable trace evidence on some fabric surfaces (Morgan and Bull, 2007). Reinforcing the recommended research focus from the UK Forensic Science Regulator, we suggest a follow-up study be conducted to determine the persistence of such transferred soil traces on the different clothing materials over time.

One requisite of the ‘ideal trace evidence’ is that the evidence should be ‘nearly invisible’ (Aardahl, 2003), however, in our experiment quite a lot of material was often visible following transfer. Denim is the only non-white material used in this experiment and soil staining was less obvious on denim, especially for the drier soils. Soil transfer may become increasingly less obvious when transferred to darker materials. If soil from a forensic scenario did result in a larger and more noticeable soil stain such as those of the saturated soils, one could assume that any perpetrator would aim to remove such a stain. It is for this reason that considering the persistence of evidence is also crucially important. One outstanding question is how much soil would remain adhered to these materials following washing, or another form of evidence diminishment. As such, we recommend future studies should test the persistence of different soils following transfer to clothing materials under different treatments to remove material. Where soil transfer is ‘nearly invisible’, or present in very small traces (e.g. following transfer of dry soil), consideration must also be given to any background traces already present on a material. There is a suggestion that the often non-sterile environments of production of some materials, can contaminate materials to an extent where background traces mask any potential signal from trace evidence (e.g. Keaney et al., 2009). It is imperative that any forensic signals are separated accurately from background traces (Stoney et al., 2016).

Methods such as washing, dry brushing and dry tag lifting to recover soil from stained clothing have all proven effective in recovering representative populations of particles from evidence material (Pirrie, 2018). Having highlighted that all clothing materials tested retained at least some soil, with most transferences allowing for multiple forensic analyses to be conducted on the collected soil, we recommend future work investigates the potential that can be recovered from soil adhering to clothing, for instance the transfer and persistence of soil palynomorphs. Much research has been done already on the inorganic fraction of forensic soils, with focusses on mineral and elemental composition specifically. Soils each possess a unique signature, and palynological profiles of the lesser researched organic fraction can prove particularly useful (Wilsthire et al., 2006; 2014). It would be greatly beneficial to determine how this palynological signature also transfers to clothing materials from forensic soils.

## 5.0 Conclusion

We present the first experimental investigation into the transfer of soils to different clothing materials, and the factors which influence the transfer of this forensic trace evidence. We conclude that soil moisture, and typically soil type have a greater influence on the amount of soil transfer, than clothing material type. Clothing material type does however have a significant influence on the transfer of drier soils. An unexpected finding was the extent to which static attraction influenced the transfer of drier soil particles to fleece material, which has previously been little explained in forensic trace studies. The key outputs from our empirical research are:

- We find all common clothing materials tested retained trace soil after brief contact with a soil surface, which is highly encouraging for the forensic analysis of soils recovered from clothing;
- Our findings confirm the important influence of soil moisture on the quantity of soil transferred during contact;
- The relative influence of clothing material type on soil transfer decreases with increasing soil moisture;

- 225 stock images of soil transfer to common clothing materials under different soil conditions have been created;
- We suggest forensic investigators may consider using different techniques to retrieve soil from different clothing materials;

We recommend further study is conducted into the transfer and persistence of soils, and the lesser researched soil palynomorphs, to clothing materials.

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