ABSTRACT

Title of Document: FORENSIC GEOLOGY IN THE URBAN ENVIRONMENT: AN ASSESSMENT OF MATERIAL TRANSFER BEHAVIOR

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Soils and related anthropogenic materials are encountered as evidence in criminal investigations. The aim of this study was to better our understanding of soil transfer behavior in an urban environment, and to evaluate the effects of sampling and material transfer on the outcomes of forensic analyses. The underlying question was whether there is a preferential transfer of urban soil material to shoes according to the tread gap distribution. During the course of this work, control soil samples from the District of Columbia were characterized and compared with soil material that had been transferred to shoes with different tread gap distributions. Soil color, particle size distribution, and mineralogy were all discriminatory among the locations in this study. Results suggest that soil color and particle size distribution are significantly influenced by the transfer process, and further study is needed to analyze the effect of single influencing factors on the resultant material.

FORENSIC GEOLOGY IN THE URBAN ENVIRONMENT: AN ASSESSMENT OF MATERIAL TRANSFER BEHAVIOR

By

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Chapter 1: Background

Forensic geology pertains to the application of geological concepts and analytical techniques to criminal and civil investigations. Geological materials involved in forensic analyses include rocks, soils, minerals, hydrocarbons, and glass, along with any other solid anthropogenic materials that have been incorporated in the earth (e.g. concrete). Forensic geology is multidisciplinary in nature, combining pedology, mineralogy, geochemistry, geophysics, molecular biology, and forensic science (Fitzpatrick et al., 2008).

Soil Formation and Horizonation

A fundamental understanding of soil science is critical in forensic geology. By definition, soil is a mixture of inorganic and organic matter that is capable of supporting plant growth. The organic matter is a combination of decayed plant and animal material, and is commonly referred to as humus. The inorganic component is a mixture of minerals and, especially in the urban environment, includes anthropogenic material such as glass, brick, or concrete. Soil material is comprised of pore space (occupied by air and water) and soil solids (occupied by mineral material and organic matter). Undisturbed soil contains 15-35% air, 40-48% mineral material, 15-35% water, and 2-10% organic matter (Schaetzl and Anderson, 2005). Soil solids are classified according to diamete r following the USDA standards: sand (0.06 – 2.00 mm), silt (0.002 – 0.06 mm), and clay (< 0.002 mm). Soil texture is the relative proportions of sand, silt, and clay-sized grains within a sample (Figure 1).

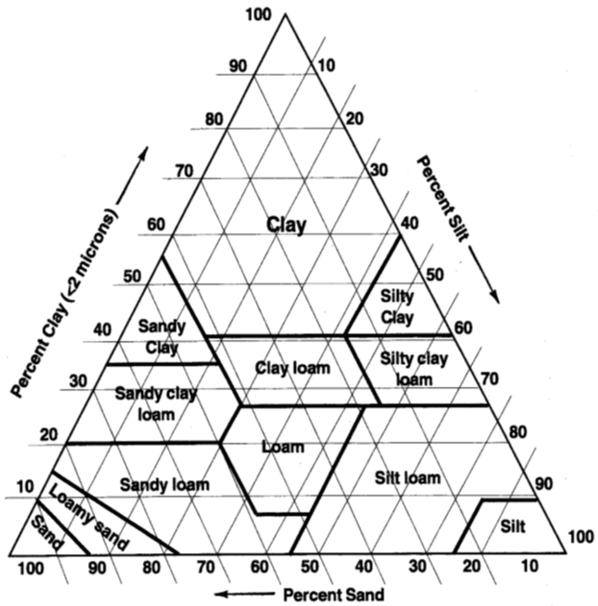

Figure 1 Soil texture ternary diagram. The soil texture ternary plot is an excellent tool for characterizing soil grain size distribution in the field. (Soil Survey Division Staff, 1993.)

Early soil scientists Vasiliy Dokuchaev and Hans Jenny greatly contributed to the ideas of how a soil forms. Dokuchaev popularized the idea that soils are not stable, inert materials, but rather develop and evolve over time under the influence of climatic, biological, and geological influences (Schaetzl and Anderson, 2005). Using these variables, Dokuchaev created the first equation of pedogenesis using the four factors of soil formation: parent material, climate, topography/relief, and biological influence. Approximately 40 years later, Jenny adapted the soil-forming equation to include time and other external soil-forming influences (e.g. anthropogenic). The work of Dokuchaev and Jenny provide much of the foundation for pedology and pedogenesis. The soil-forming equation states that soil (s) is a function of these 5 factors.

$$s = f\,(cl, o, r, p, t)$$

Equation 1 Soil-forming equation with factors climate (cl), organisms (o), topography (r), parent material (p), and time (t).

Most soils exhibit a layering of accumulated material, a feature termed horizonation. A layer formed by pedogenic (soil forming) processes that is approximately parallel to the soil surface is called a soil horizon. Each distinct soil horizon possesses significant differences in characteristics (color, texture, or mineralogy) when compared to the horizons above and below it. The soil horizons, starting at the surface, are named O, A, E, B, C, and R. Originally defined by Charles Edwin Kellogg in 1936, the solum includes the portion of the soil profile that has been altered by pedogenic processes and includes all of the profile above the C horizon (weathered bedrock) (Schaetzl and Anderson, 2005). Soil horizons form within unconsolidated materials, such as weathered bedrock, on stable surfaces that have been exposed for a sufficient length of time. Soil horizons are products of material being added to or removed from parent material, and form as material is translocated within the profile or as it is transformed *in situ* (Simonson, 1959). The major horizons of a soil profile and their characteristic properties are listed in Table 1.

Soil profiles are classified based on the characteristics present in a pedon – the standard size for characterizing a soil profile, ranging from 1 m^2 to 10 m^2 (Schaetzl and Anderson, 2005). The pedon is the smallest soil body that retains all the major variability of the soil. Due to the majority of criminal activity occurring on the surface of the earth, forensic geology primarily deals with the O and A horizons.

Horizon	Thickness (Inches)*	Characteristics
O	0-2	Dominated by decomposing organic matter (humus).
A	2-13	Accumulation of humus mixed with the mineral fraction or has properties resulting from agricultural or similar kinds of anthropogenic activities.
E	4-10	Eluvial horizon: light-colored mineral horizon due to the loss of weatherable minerals, silicate clay, iron, aluminum, and/or humus. This results in a concentration of uncoated quartz grains or other resistant minerals (giving the light or 'clean' color).
B	10-24	Dominated by illuvial accumulations of clay, iron, or aluminum.
C	12-41	Minimally affected by pedogenic processes and lack properties of O, A, E, or B horizons. Most C horizons retain some rock structure. Also known as saprolite.
R	>41	Unweathered bedrock (parent material).

Table 1 Soil profile horizons and their respective defining characteristics. Modified from Guthrie and Witty (1982). *Soil horizon thickness can vary according to any of the soil forming factors: soil age, parent material, geographical climate, topography, biological activity, or any combination of the aforementioned factors. The soil horizon thickness ranges in this table are representative of the soils used in this study.

Soil Mineralogy

An important step in the formation of soil from bedrock involves weathering of the rock into smaller and/or chemically altered parts (Schaetzl and Anderson, 2010). To a variable extent, rocks are physically and chemically unstable at the Earth's surface because the Earth surface environment is usually different from the conditions under which they formed. Compared to rock-forming conditions, the surface environment is almost always colder, and lower in pressure; further, the activity of water, and in particular, oxygen, is commonly higher. As a result of these conditions, biological activity is also high at or near the Earth's surface. Weathering, the process by which rocks move toward a state of equilibrium under surficial conditions, is the physical and chemical alteration of rocks and minerals at or near the Earth's surface, which is driven by biological, chemical, and physical agents (Pope et al., 2002). As a result of weathering, rocks change mineralogy, chemical composition, texture, color, and strength. In general, the effects of weathering are more pronounced as distance from the bedrock increases.

Minerals are classified according to their chemical composition, crystal structure, and whether they are primary (igneous) or secondary (sedimentary or metamorphic) (Jackson, 1964). Many primary minerals are unstable within soils and weather to secondary minerals because they form in an environment that is different from the Earth's surface. The minerals within a soil form as a result of several processes of weathering, including oxidation, reduction, dissolution, hydrolysis, dehydration, and cation exchange. The following mineral reactions below represent a small portion of those that occur during the soil-forming process (from Bricker et al., 1968). In reactions 1 and 2, the primary mineral oligoclase partially weathers to kaolinite and gibbsite:

(1) $NaAlSi_3O_8^{(oligoclase)} + 7H_2O + H^+ \rightarrow Na^+ + Al(OH)_3^{(gibbsite)} + 3H_4SiO_4$

(2) $2Al(OH)_3^{(gibbsite)} + 2H_4SiO_4 \leftrightarrow Al_2Si_2O_5(OH)_4^{(kaolinite)} + 5H_2O$

Biotite is susceptible to weathering and commonly yields the clay mineral vermiculite, which can further weather to kaolinite. Reactions 3 and 4 are typical of soils forming from ultramafic parent material:

(3) biotite → vermiculite → kaolinite

Reaction 4 is an example of mineral dissolution, with no mineral end product (from Cleaves et al., 1974).

(4) $Mg_3Si_2O_5(OH)_4^{(Serpentine)} + 6CO_2 + 5H_2O \rightarrow 3Mg^{2+} + 6HCO_3^- + 2H_4SiO_4$

Soils that have been exposed to weathering processes for a longer amount of time ultimately have a lower percentage of primary minerals relative to younger soils. Primary minerals tend to dominate in coarser size fractions, whereas secondary minerals are most abundant in the clay and fine silt fractions (Schaetzl and Anderson, 2005). Nearly all major groups of soil minerals, including silicates, oxides, phosphates, carbonates, and sulfates, are solids where the cations and anions are ionically bonded. Oxygen is the primary anion in most soil minerals. The most common cations in soils are Si^{4+}, Al^{3+}, and Fe^{3+}; the abundance of these elements reflects both their concentration in the earth's crust and the relatively low solubility of their oxides and hydroxides. Additional information regarding soil mineralogy is discussed in Appendix 1.

Understanding which minerals and mineraloids are likely contained within different soil types is critical in the examination of soil evidence. Soil samples, including forensic soil samples, are commonly distinguished based on their mineralogy (Junger, 1996; Bull et al., 2006). Identifying mineral assemblages in a soil sample is an important step in forensic comparisons, and further, identifying atypical mineral assemblages within a sample may yield information capable of distinguishing or linking evidence and geographic location. Although there are thousands of types of minerals, only about 20 are common in soils; further, there are usually no more than five different species of mineral found in any given sample (Murray and Tedrow, 1992; Appendix 1).

Forensic Geology and Soil

There are two fundamental concepts in the application of soils and soil material to forensic geology. First, soils and soil material are highly variable. Properties such as color, texture, organic and inorganic matter content, and the presence and type of biological activity are not collectively the same in any two soils. This variability allows forensic geologists the potential to use soil material as a powerful discriminatory tool as evidence in a court of law. The second fundamental concept is that there will almost always be a trace of a person's presence at a location, which is summarized by Locard's Exchange Principle. Locard's Exchange Principle states that when two objects come into contact with one another, an exchange of material occurs (Murray, 2004). The regular interactions of people and objects with the ground surface create opportunities for the transfer and subsequent recovery of soil and related material (such as the urban component of soil – solid anthropogenic materials including brick or concrete) for use as a potential source of evidence (Dawson and Hillier, 2010). The urban component of soil may remain on the surface to which it transferred for an extended period of time, especially when combined with soil material (Taupin and Cwiklik, 2011). Merging these concepts allows forensic geologists to recover evidentiary material, characterize and compare that material, and determine how likely it was that a person or object was at a location of interest.

The specific goals for a forensic geological comparison study are (Murray, 2004; Bottrell, 2011):

1. Establish sample provenance or use for comparison with samples of known provenance;
2. Establish the original location of the crime (e.g. when suspected that a body or weapon has been moved from the original crime scene);
3. Establish a nexus, or lack thereof, between a suspect and a crime scene; and
4. Detect the presence of fraudulent activity (examples include determining if supposed naturally flawless gemstones have been enhanced and tracing the theft of valuable minerals and metals).

Although there are a number of studies in the literature involving the characterization of soil for forensic purposes, relatively few discuss the transfer of soil to items of forensic interest (e.g. shoes, clothing, vehicle tires). Consequently, the effect of Locard's Exchange Principle is markedly absent from the scientific literature. There is a need for an increased knowledge of the mechanisms of the soil transfer process from the ground to these items of forensic interest. The motivation for this study lies in the importance of understanding how soil characteristics (e.g. color, particle size distribution, and mineralogy) change as a result of the soil transfer process, and whether these changes can be quantified and corrected for in forensic analyses.

Chapter 2: Introduction

Soils, sediments, and urban materials can be the subjects of forensic trace evidence analysis (Dawson and Hillier, 2010; Fitzpatrick, 2009, Murray and Solebello, 2009; Rawlins et al., 2006; Bull et al., 2006). Given this importance, research is needed to evaluate the effects of sampling and material transfer on the outcomes of forensic analysis. As part of this study, the transfer of soil material between the ground surface and the shoes with varying tread gap size distributions (a biased Locard exchange) will be evaluated. Additionally, as a part of this work, intra-site and inter-site soil variation within the District of Columbia will be assessed.

Previous Studies in Forensic Geology

Currently, there is no commonly accepted protocol for analyzing soil samples in the laboratory (Dawson and Hillier, 2010, Fitzpatrick, 2009). This is due, in part, to the fact that no two crime scenes are exactly the same. Environmental factors, the severity and nature of the crime, and the amount and type of evidence available often widely vary between any two cases. Additionally, no two soil samples have the exact same characteristics. Because of the variability between crime scenes and laboratory resources, the type of evidence and analytical techniques used cannot always be the same. Common methods used in soil evidence analysis include binocular microscopy, determination of color, and determination of chemical compositions via scanning electron microscopy and energy-dispersive x-ray spectroscopy (Dawson and Hillier, 2010). Although there is a large degree of inconsistency between evidentiary material and analytical methodology used in analyses, it is universally agreed upon that to obtain the most accurate results, multiple techniques should be used when comparing soil material. The combination of techniques used is dependent upon several factors, including sample size, time constraints, cost limitations, availability of laboratory equipment, and laboratory personnel qualification (Croft and Pye, 2004a).

A study by Croft and Pye (2004a) characterized soil material according to color, particle size distribution, stable carbon and nitrogen isotope ratios, and soil composition to compare undisturbed soil sample (‘source’) with soil material that has been recovered from shoes (‘transfer’ soil samples). They used four soil types and five footwear types. Croft and Pye chose locations to represent a range of soil types and the shoes chosen were based on those commonly encountered in forensic laboratories. The shoes included three types of boots, a pair of Lacoste shoes, and a generic trainer. Although it was observed that there were only relatively small differences between the undisturbed and transferred soil material with respect to the color, isotopic, and chemical analyses, significant differences were found in the particle size distribution patterns, indicating that the primary transfer process is particle-size dependent. Although the Croft and Pye study focused on determining how soil properties are affected as the material transfers to footwear, it was not concerned with footwear specifics such as tread distributions or percentage of shoe sole with the potential to come into contact with the ground with each step (the treads). Compared with the objectives of Croft and Pye, the current study is focused on observing the effects of soil material transfer behavior as a function of shoe tread size distribution, an important characteristic not addressed in previous studies. Additionally, in the aforementioned study, Croft and Pye only characterized the soil samples within the <150 µm fraction; this study will provide detailed analysis according to several size fractions, including >130µm, 130-60 µm, 60-41 µm, and <41 µm. These particle size bins were chosen for this analysis based on the findings of Croft and Pye, 2004a, 2004b; Palenik, 2007; Junger, 1996; Chazottes et al., 2004; and Sugita and Marumo, 2001; and, Guedes et al., 2009. A discussion of these studies relating to the particle size bins in this research is given in Appendix 3.

In a similar study, Chazottes et al. (2004) compared particle size distribution patterns between undisturbed (control) and transferred soil material as a function of soil type and transfer medium at simulated crime scenes. Soil material adhering to two types of footwear (boots and sport shoes) was compared with control samples using particle size analysis. The aim of their study was to determine how the particle size distribution of soil material recovered from different objects, including tissues, boots, and shoes, compared to the source material, and to investigate whether differences among soil samples from the same source overlapped with differences among soil material from a different source. Two types of soil were sampled: one from a glacial deposit, rich in very fine and coarse-grained fractions (having a bimodal distribution), and the other from a weathered gneiss, rich in medium-sized particles. In both soil types, the particle size distribution of the material recovered from the boots was similar to the source material, whereas the distribution from the sneakers generally showed a loss of the coarsest fraction (> 1,000 µm) and an enrichment of the finest fraction (< 20 µm). Further, they found that even though the differences were only attributed to the extreme size fractions between the control and transferred material, when samples from different sources were compared, there were also significant differences in the medium size classes. Due to the vulnerability of the extreme size fractions seen in this study and the persistence of the middle size fractions, it is suggested that the most useful range of particle size for forensic analyses is 1,000 µm to 63 µm.

The above study suggests that the differences in particle size distribution were not random, but rather dependent upon the properties of the shoe surface to which it adheres; for example, the large tread of the boot (1-2 cm gap) accumulated soil material that was more representative of the original source material compared to the finer treads seen in the sport shoes. Although Chazottes et al (2004) addressed the issue of how shoe tread size may affect soil material transfer, it was not studied in-depth; other than characterizing the shoe according to style (boot, athletic shoe), there was no information about the surface to which the soil transferred to (e.g. the shoe sole). Understanding the details of the object surfaces to which soil transfers is inherently important to studying the nature of the soil transfer process. Additionally, particle size distribution was the only characterized property. As indicated by Morgan and Bull (2007a, 2007b), particle size analysis can be a useful descriptive tool, but its current use in forensic analysis should be taken with caution, especially when no other characteristics are to be analyzed, as is the case in the above study. That is, in most forensic cases, soil material encountered during the investigation process has been transported from the original crime scene to another object, such as a pair of shoes, clothing, tires, etc. This may introduce complex biases due to sediment mixing (Morgan and Bull, 2007b). As confirmed by many authors (Croft and Pye, 2004a, 2004b; Taupin and Cwiklik, 2011; Bull and Morgan, 2006; Fitzpatrick and Raven, 2009), there is a need for the effect of these transportation mechanisms to be studied. This study sought to identify the presence and extent of soil transfer biases, with the intention of using these results to improve forensic analyses.

Soil color measurement, particle size distribution, and/or phase identification studies are common in forensic geology and trace evidence analysis literature. The combination of the methods and goals in this study, including characterizing the shoes according to tread size distribution and the focus of conducting the study in an urban environment allows for a better understanding of soil and urban material transfer behavior.

Chapter 3: Regional Geology

The geological provinces within the District of Columbia include the Coastal Plain and the Piedmont. The Fall Zone (or Mid Atlantic Fall Zone) separates the Piedmont Province on the west from the Coastal Plain Province on the east, and bisects the District diagonally from northeast to southwest (DC Water Resources Research Center, 1992).

The Potomac terrane of the easternmost Piedmont Province is present in the District of Columbia, and comprises igneous and metamorphic rocks derived from sedimentary and intrusive igneous rocks. The Potomac terrane is bounded on the west by the Pleasant Grove fault and is covered by Cretaceous and Tertiary Coastal Plain deposits to the east. The mapped units of the Potomac terrane, from west to east, are the Mather Gorge, Sykesville, and Laurel Formations. The protoliths of these rocks are interpreted to be Neoproterozoic to Early Cambrian slope deposits and olistostromes (underwater mélanges). These formations include mélanges that contain ultramafic rocks, and are intruded by Early to Middle Ordovician tonalites and granodiorites. Dominant lithologies include schist, phyllite, quartzite, altered mafic and ultramafic rocks such as greenstone and serpentine, gneiss, and intrusive granites and quartz diorites (DC Water Resources Research Center, 1992).

East of the Fall Zone are the sediments and rocks of the Coastal Plain. The Coastal Plain formations are largely unconsolidated and range in age from the Cretaceous period to the present. As the Piedmont Province weathered, streams carried sediment, which became the foundation of the western Coastal Plain, whereas the easternmost formations were deposited in a shallow marine environment. The formations tilt away from the Piedmont Province and usually become thicker and younger as they approach the Atlantic Ocean.

The three locations used in the study are public access areas located at Rock Creek Park, Sherman Circle, and Marvin Gaye Park (Figures 2, 3). These locations were chosen for three reasons: 1) they are widespread across the District of Columbia, 2) some are significant to forensics in terms of criminal activity (Marvin Gaye Park), and 3) access to collect samples. Access to samples applies in that D.C. is an urban metropolis with areas covered by up to 90-100% impermeable surfaces (e.g. roads and sidewalks), which inhibit extensive sample collection (Woods Hole Research Center).

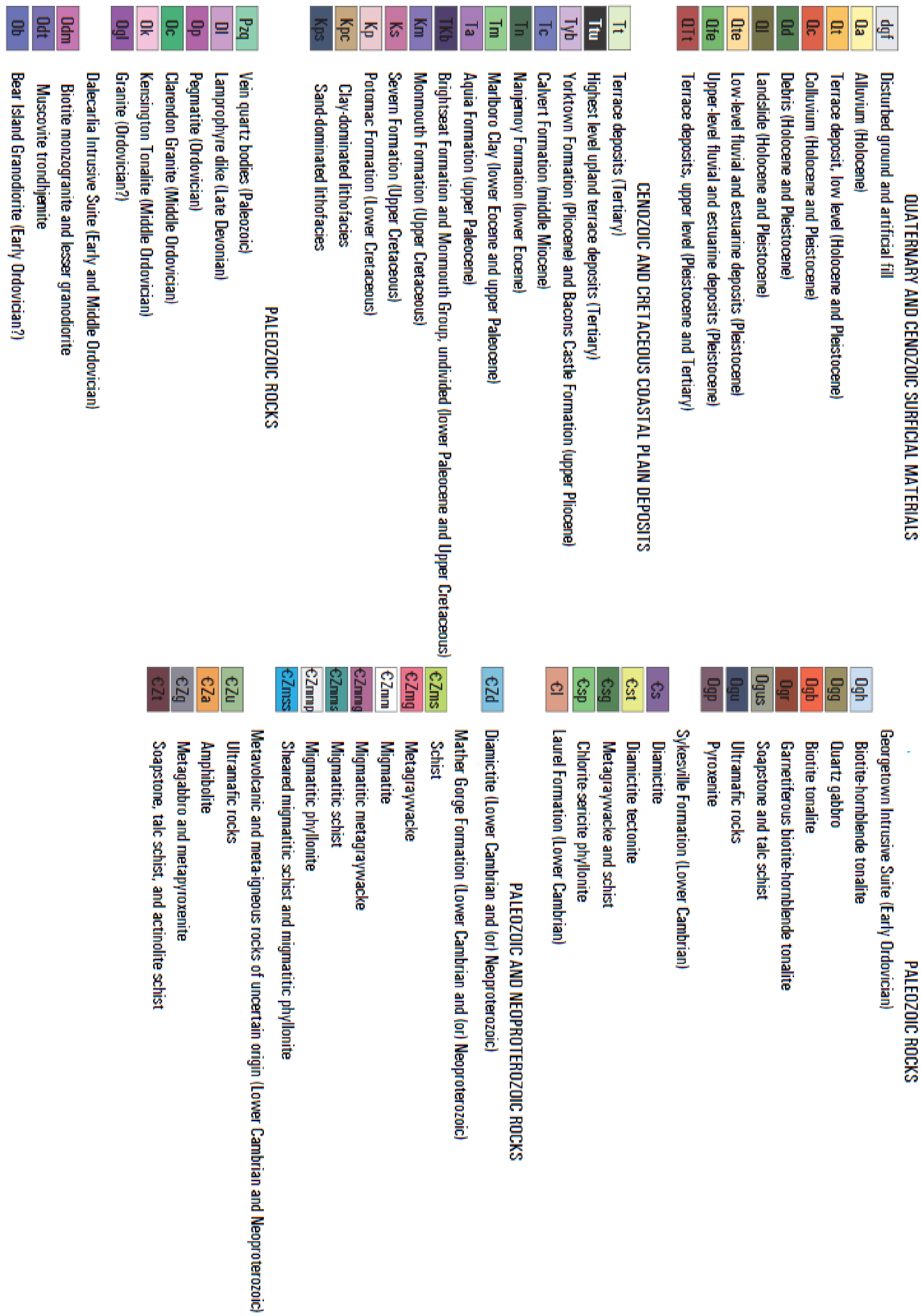

Figure 2 Geological map with legend of the District of Columbia. Stars indicate soil sample location: blue – Rock Creek Park, yellow – Sherman Circle, orange – Marvin Gaye Park. Map from Southworth and Denenny (2005).

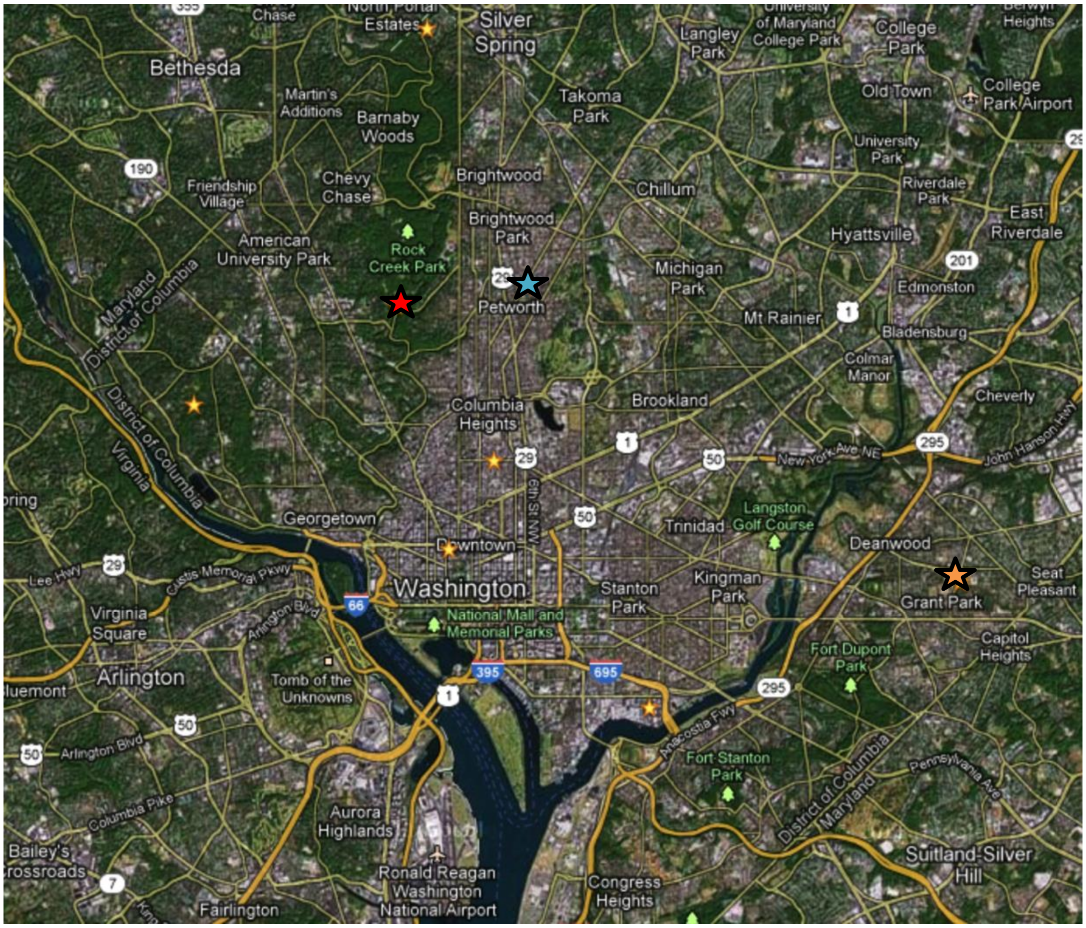

Figure 3 Aerial map of the District of Columbia. Sample locations are marked with stars: Rock Creek Park (blue), Sherman Circle (yellow), and Marvin Gaye Park (orange). Magnetic mineral collection sites are marked as green circles. Image last accessed August 15, 2012 from Google aps.

Rock Creek Park

The Rock Creek Park sample site lies west of the fall zone and consists of the Lower Cambrian Laurel Formation (€l), Early Ordovician garnetiferous biotite-hornblende tonalite of the Georgetown Intrusive Suite (Ogr), and Tertiary Coastal Plain deposits (Tt) (Figure 2). The nearby Rock Creek shear zone (Figure 4, below) separates the rocks of the Sykesville Formation on the west from the Laurel Formation on the east (Kunk et al., 2004). The Rock Creek shear zone represents one of the edges of the fall zone that separates the Piedmont and Coastal Plain provinces.

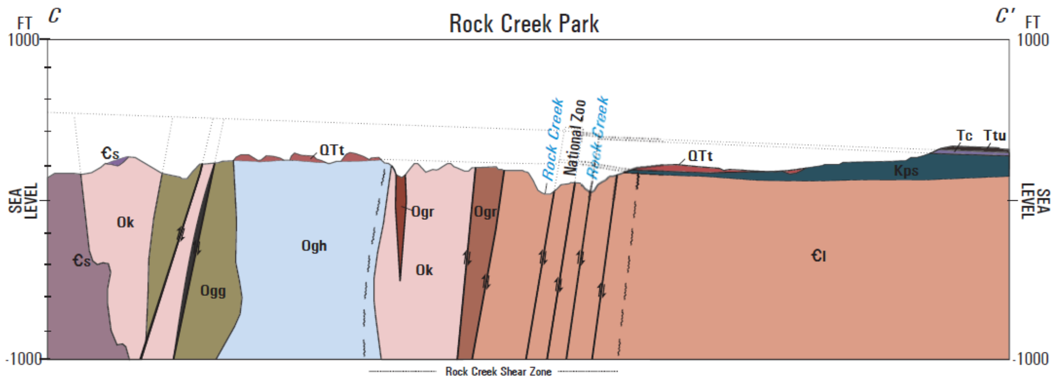

Figure 4 Cross-sectional view of the geology of Rock Creek Park. Map from Fleming et al. (1994). See Figure 2 for the key to formation abbreviations.

The protolith of the Laurel Formation is a diamictite, interpreted as being a sedimentary mélange with clasts of quartz, biotite schist, and actinolite schist, and is supported by a quartzofeldspathic matrix (Fleming et al., 1994). Ultramafic rocks (e.g. serpentinites) are also prominent. The eastern Laurel Formation (closest to the sample site) is covered by Cretaceous and Tertiary Coastal Plain sediments.

Figure 5 Soil map of Rock Creek Park sample location and surrounding area. Location marked with blue star. Map from USDA Web Soil Survey.

The Codorus-Urban land complex soil series (Cn) dominates the Rock Creek Park location (Figure 5). Codorus soils formed on floodplains and have a loam-to-silt loam texture. These soils formed in alluvial deposits containing metamorphic rocks such as schist, gneiss, phyllite, and serpentinite. Serpentinites are hydrothermally-altered peridotites. In the idealized reaction below, olivine (forsterite) is hydrothermally altered to serpentine (chrysotile) and brucite. This reaction occurs at temperatures below 400° C. Some iron is present in the olivine, which may enter the structures of serpentine and brucite as they form.

$$2\ Mg_2SiO_4 + 3\ H_2O \rightarrow Mg_3Si_2O_5(OH)_4 + Mg(OH)_2$$

As a result of the serpentine weathering, some iron will become incorporated into the brucite structure; however, much of this iron yields magnetite (Moody, 1976).

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + 2H_2O + H_2$$

Other than the minerals of the spinel group such as chromite and magnetite, the majority of minerals in ultramafic rocks weather easily. For example, even though brucite is a major product of the reaction above, it is not common in soils because of its high solubility. Many serpentine minerals also weather easily and are not present in the clay fraction, even in very young soils (Wildman et al., 1968; Rabenhorst and Foss, 1981). The most abundant clay minerals found in the initial stages of pedogenesis from ultramafic rocks are chlorites and smectites (Ducloux et al., 1976). Chlorite and smectite minerals, in addition to vermiculite, are common in Maryland soils formed from ultramafic rocks (Rabenhorst et al., 1982). Given the large influence of serpentinite and alluvial deposits at the Rock Creek Park sample site, minerals in the > 41 µm size fraction at this location include quartz, feldspars, magnetite, serpentine, and other ultramafic-derived minerals that are resistant to weathering.

<u>Sherman Circle</u>

The Sherman Circle sample location is east of the Mid Atlantic Fall Zone and consists of a sand-dominated lithofacies of Cretaceous Coastal Plain deposits (Kps).

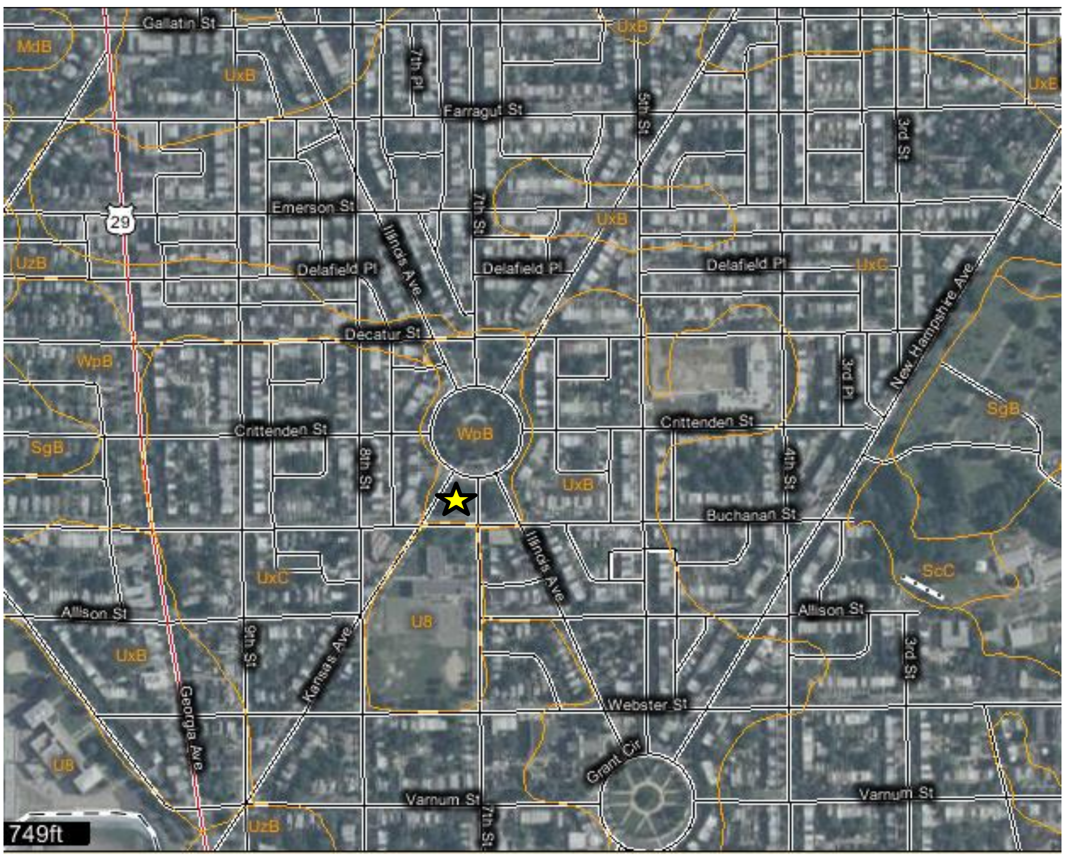

Figure 6 Soil map of Sherman Circle sample location and surrounding area. Location marked with yellow star. Map from USDA Web Soil Survey (1993).

The soil series present at the Sherman Circle location is the Woodstown-Urban land complex (WpB) (Figure 6). The Woodstown soil series is on the western boundary of the Coastal Plain Province and is formed from sandy marine and old alluvial sediments.

Marvin Gaye Park

Marvin Gaye Park also lies east of the Mid Atlantic Fall Zone. The lithology of Marvin Gaye Park sample location consists of a clay-dominated lithofacies of Coastal Plain deposits (Kpc), upper-level terrace deposits of the Pleistocene and Tertiary (QTt), and lower-level terrace deposits of the Holocene and Pleistocene (Qt).

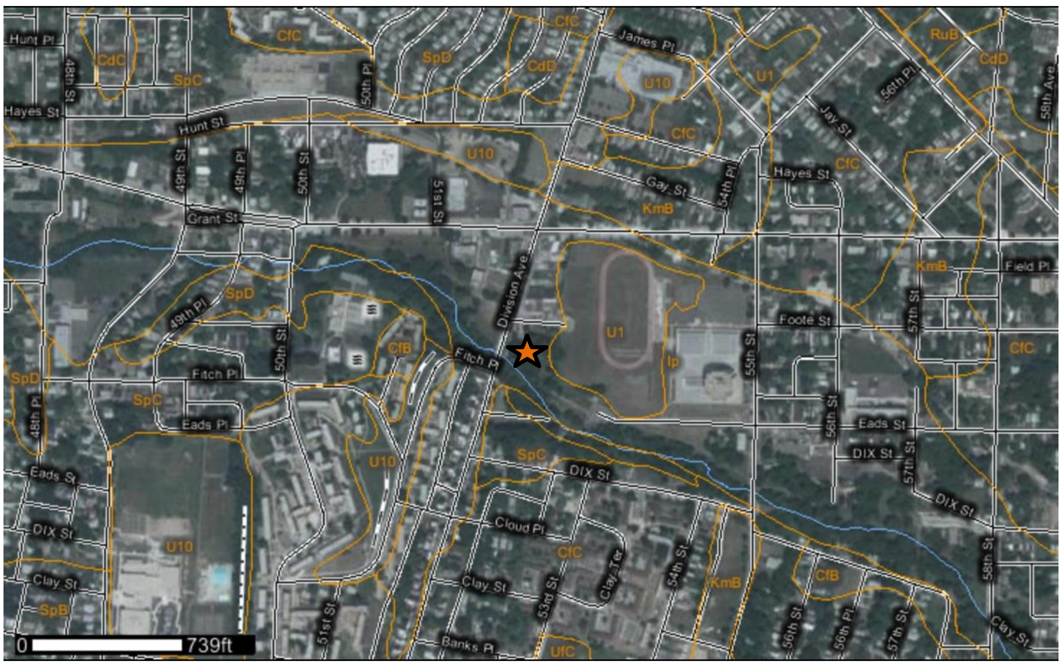

Figure 7 Soil map of Marvin Gaye Park sample location and surrounding area. Exact location marked with orange star. Map from USDA Web Soil Survey (1993).

The Sunnyside-Urban land complex (SpC) and Iuka-Urban land complex soil series (Ip) present at Marvin Gaye Park consists of very deep, well-drained moderately permeable soils on the inner portion of the northern Atlantic Coastal Plain (Figure 7). Similar to the soil series at the Sherman Circle location, these soils formed in unconsolidated loamy and sandy fluvial sediments.

The parent materials of Sherman Circle and Marvin Gaye Park are nonmarine Coastal Plain sediments that are derived from the rocks of the Piedmont. Atlantic Coastal Plain sediments may include clay minerals such as kaolinite, illite, vermiculite, and muscovite (Groot and Glass, 1960). Nonmarine Cretaceous sediments are also characterized by a lack of or absence of montmorillonite and chlorite (Groot and Glass, 1960). The heavy mineral suite of nonmarine Cretaceous Coastal Plain sediments is distinguished by its limited mineral assemblage, being dominated by zircon, tourmaline, and rutile (Groot and Glass, 1960). Compared to the source material, the heavy mineral suite of these Cretaceous nonmarine sediments lack garnet, hornblende, chloritoid, and epidote (Groot and Glass, 1960). It can be inferred that the mineralogy of a location will change with differential weathering and increasing distance from the source material; distance from the source material to sample location increases in the order Rock Creek Park → Sherman Circle → Marvin Gaye Park. Therefore, it is likely that there will be a decrease in the number of minerals that match the source material, in both the bulk soil and heavy mineral fraction, from Rock Creek Park to Sherman Circle to Marvin Gaye Park.

Chapter 4: Methodology

The methodology in this study is divided into two parts: collection and characterization of undisturbed soil samples; and, transfer of soil material to shoes and the characterization of that material. Sample locations and analytical methods are introduced and discussed in Part I, whereas information regarding the shoes used in the study and soil transfer mechanisms are discussed in Part II.

Part I: Undisturbed Soil Sample Collection and Characterization

Based on the findings of Pye et al. (2006), a minimum of three, but preferably five or more samples should be collected from any location of forensic interest to determine the intra-site variation. In this study, six samples were collected from each of the three locations: an area immediately south of Sherman Circle in Northwest D.C. (Figure 8), Marvin Gaye Park in Northeast D.C. (Figure 9), and Rock Creek Park in Northwest D.C. (Figure 10). These locations were chosen based on several factors, including differences in soil composition, access to sampling, and in one case, proximity to criminal activity in the area (Metropolitan Police Department Annual Crime Totals 2011). Weather conditions during sample collection were recorded in order to establish if there was any relationship between temperature, season, or time of day and soil accumulation onto the shoes. Information about weather conditions during soil sample collection is given in Chapter 6.

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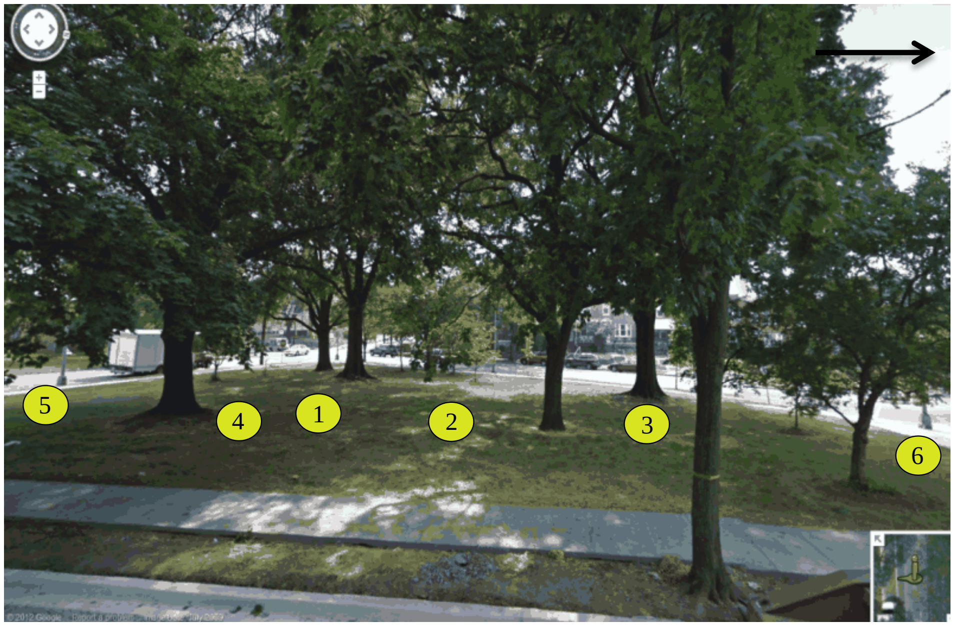


Figure 8 Street view of the Sherman Circle location. Image last accessed May 3 2012; arrow pointing to North.

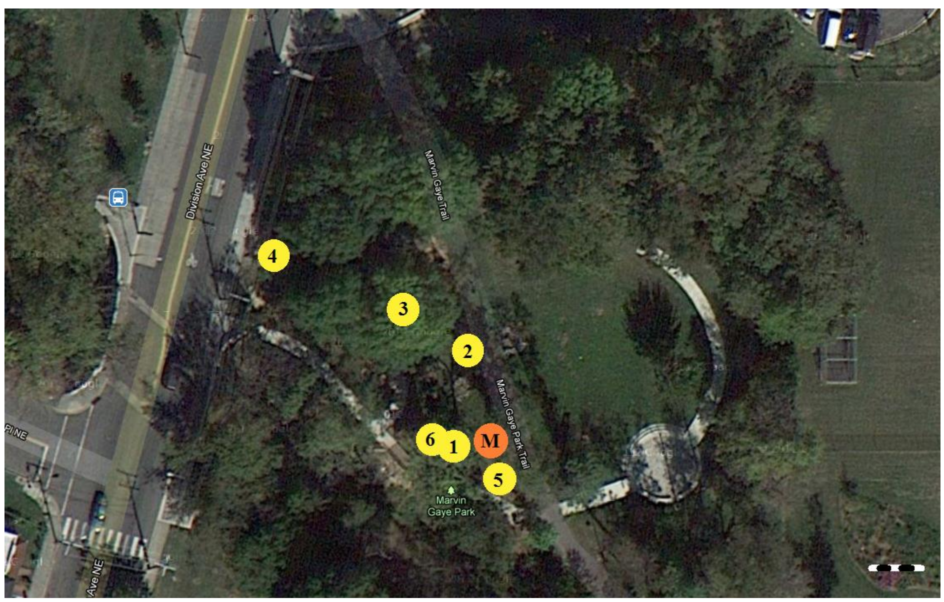


Figure 9 Sample locations (1-6 and magnetic fraction “M”) at Marvin Gaye Park. Scale bar 20 feet.

Figure 10 Rock Creek Park. Length of path in photo is approximately 30 feet.

Figures 11 (left) and 12 (right): Ground surface before (left) and after (right) undisturbed soil sample collection at Sherman Circle. Soil properties such as texture and color at the surface may vary significantly from those at a depth as shallow as a few centimeters.

Upon visual inspection, the soil at Rock Creek Park did not exhibit any noticeable variation in color or dominant particle size across the area, and samples were collected along a linear transect. The soil properties appeared to vary at Sherman Circle and Marvin Gaye Park, and therefore soil samples were collected with the intent to capture this variability across the area. Each sample was collected no more than 1 inch deep to preserve the characteristics of soil most commonly encountered in criminal investigations (Figures 11, 12), although it should be noted that different depths of soil are appropriate for sampling depending on the nature of the crime. Post-collection, the samples were characterized in the laboratory in the following order: undisturbed soil sample color, particle size distribution, individual size fraction color, heavy mineral separation, microprobe analyses, which includes both scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS), and x-ray diffraction (XRD).

Soil Color

Soil color was measured using a Konica Minolta CR-300 digital colorimeter (Figure 13). The measuring head of the CR-300 uses a pulsed xenon arc (PXA) lamp, which provides diffuse, uniform lighting over an 8mm-diameter specimen area. Before use, the colorimeter is calibrated to a white ceramic tile. Results from the colorimeter are given in several different color systems. For this study, the L* a* b* system was used because it provides values according to a three-dimensional color space which can easily be plotted for sample comparison. The different values correspond to a sample's lightness or darkness (L*), red-green component (a*) and blue-yellow component (b*). Additionally, these measurements provide insight to sample

Figure 13 Konica-Minolta CR-300 digital

mineralogy: higher L* values may correspond to more quartz, muscovite, or feldspar in a sample, whereas lower L* values may be indicative of more organic matter, biotite, or other ferromagnesian minerals. Higher a* values are characteristic of more red minerals such as iron oxides or potassium feldspars, and lower a* values indicate the presence of green minerals such as chlorite, serpentine, or epidote, etc. Higher b* values may indicate a prominence of sulfur-bearing minerals, whereas lower b* values indicate the presence of blue minerals such as glaucophane or riebeckite (Figure 14). Soil color was measured on two different types of samples during the study: undisturbed samples (pre-sieving) and individual size fractions (post-sieving). All samples were dried at 110º C and stored in a sealed container until immediately before taking the color measurements. For comparison to soil color, L*a*b* color values for various geological materials are listed in Appendix 13.

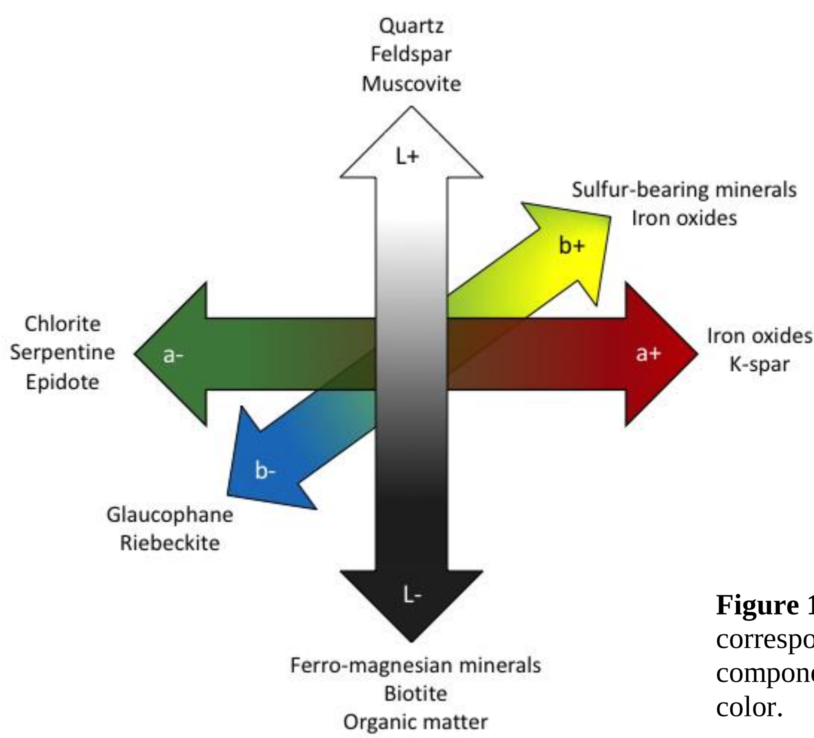


Figure 14 L* a* b* color system corresponding to likely soil components that can influence color.

Color measurements were collected for each of the individual size fractions, and for the undisturbed sample, in order to determine if and how soil color changes as a function of grain size. Samples received as forensic evidence may have different properties (such as color and particle size distribution) than the original undisturbed material. For this reason, it is important to collect data on properties (e.g. soil color) of the individual size fractions (Taupin and Cwiklik, 2011). Results of soil color differences obtained in this study are presented in Chapter 6.

Particle Size Distribution

Soil particle size distribution is achieved by sieving the undisturbed soil samples. Prior to sieving, particles larger than 1 cm, and organic matter such as twigs, grass, bark, etc., were removed. As this is an alteration of the original sample, any removal of particles in the soil was noted and the particles themselves were preserved. The samples were oven-dried at 110° C overnight to remove moisture, and then afterwards, the dried samples were then weighed to give an initial reference weight. This temperature is what has been, or is very close to, the temperature reported in the literature for removing moisture from soil samples (Dudley, 1975; Murray and Sollebello, 2009; Junger, 1996). Additionally, 110° C is above the boiling point of water (100° C), which will drive off any soil moisture within a soil, but is not high enough to change any prominent features of the soil, including color or mineralogy. Soil color will change if any organic material adhering to mineral grains burns; and, the loss of inter-layer water from clay minerals has been reported at temperatures as low as 220° C (Emmerich et al., 1999). Samples were weighed on a Mettler Toledo

XP105 DeltaRange analytical balance, which was determined to have an uncertainty of $\pm$ 0.1 mg.

The method of wet sieving was chosen because it allows for any clumped soil material to be disaggregated without compromising grain integrity. The sieving apparatus was constructed using a 3-inch diameter PVC pipe of approximately 6 inches in length fit into a straight connector (Appendix 12). For each size fraction, squares of the corresponding sieving mesh, approximately 4"x 4" in area were placed between the PVC pipe and connector. This apparatus was put into a 1,000 mL beaker, and the soil sample was poured into the PVC. The emptied container was then held over the PVC sieve and rinsed with distilled water to maximize the recoverable soil material in the sieving process. Distilled water was slowly poured over the sample until the water running through the disposable mesh ran clear to the naked eye. The soil was stirred with a glass rod rinsing. After the water ran clear, the sieve, holding the portion of the sample that did not pass through the mesh, was placed inside a petri dish lid, and the suspension was poured into a 100 mL or 250 mL beaker, depending on the volume of suspension. These beakers had been weighed previously, while empty, so that the oven-dried soil weight could be obtained from the same beaker. This process of weighing minimized any sample loss during the sieving and drying process. The PVC pipes were then disconnected and replaced with a new mesh of the next size, then placed in a second 1,000 mL beaker, and the process repeated, using the sample that had not passed through the previous mesh.

After each fraction was isolated, the samples were re-dried in the oven at 110° C and re-weighed, allowing the measurement of particle size distribution percentage by weight. LabPak© disposable mesh was used as the sieving medium. The size bins used for sieving in this study are (in μm): >130, 130-60, 60-41, and <41. A discussion of the use of these size fractions is given in Appendix 3. These fractions allow for a detailed analysis of the sand fraction (medium, fine, very fine sand) as well as information on a combined silt and clay fraction of soil samples. The <150 μm fraction has been observed to contain the most useful portion of the soil sample for forensic purposes (Croft and Pye, 2004a; Guedes et al., 2009; Pye et al., 2006), so there is a limited need for the >150 μm fraction. A commonly used lower limit for particle size bins is 63 μm (Junger, 1996; Guedes et al., 2009; Sugita and Marumo, 2001; Wanogho et al., 1989). In this study, 60 μm was used instead of 63 μm because of the ease of obtaining the sieving materials. The 130-60 μm fraction was chosen for the heavy mineral analysis based on the findings on Junger (1996) and Palenik (2007).

Heavy Mineral Separation

The identity of heavy minerals (>2.96 g/cc) in a sample may yield useful information about sample provenance. The relatively low concentration of heavy minerals in samples can be a limitation in forensic soil analysis because the same suite of heavy minerals may not be present in two samples taken at the same source site (Morgan and Bull, 2007b). During heavy mineral analysis, it is important to note the presence of a phase,

Figure 15 Heavy mineral separation: a sample is settling in tetrabromoethane.

as well as mineral shape and surface texture, which may be indicative of geological environment. The combination of the heavy mineral assemblage, together with the grain shape and surface texture, can strengthen the determination of sample provenance.

Upon preliminary visual examination, the larger size fractions showed high percentages of light minerals such as quartz and feldspars, and low concentrations of heavy minerals, a result that is consistent with published studies. In this study, the 130–60 µm size fraction was chosen for heavy mineral separation. Heavy mineral fractions were isolated using tetrabromoethane ($C_2H_2Br_4$), which has a density of 2.96 g/cm^3 at standard temperature and pressure. The liquid was poured into a 500 mL separatory funnel and then the appropriate size fraction was added to the liquid. The mixture was stirred with a glass rod to break up any coalesced material and the sample was allowed to settle overnight to obtain maximum separation of heavy minerals. The heavy minerals sink to the bottom of the separatory funnel and were isolated by opening the stopcock and allowing the grains to collect in the filter paper while the excess liquid drained into a beaker (Figure 15). The heavy minerals were then rinsed with acetone to wash away any remaining heavy liquid, and were prepared for scanning electron microscopy and energy dispersive spectroscopy.

SEM and EDS

Scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) were used in combination to obtain information about the heavy mineral fraction chemistry and textures. These techniques were used to characterize the elemental composition of particles, and were commonly used together with backscattered electron imaging, which provided another method for identifying unusual or diagnostic particles and mapping the extent of their distribution (Dawson and Hillier, 2010). These analyses aid in determining the mineralogy and identifying any anthropogenically-introduced material, which, especially in the analysis of an urban soil, has the potential to be particularly useful for site characterization (Dawson and Hillier, 2010). If present, distinctive minerals, mineral assemblages, textures, or other identifying features are exclusive to a location, and therefore, an appropriate discriminatory feature in forensic analyses.

X-ray Diffraction

X-ray diffraction (XRD) analyses were conducted on the undisturbed soil samples of the three sample locations as well as on individual size fractions from Rock Creek Park. The x-ray diffraction patterns of the soil samples from the different locations can be used as a 'fingerprint' identifier. XRD analyses have previously been discussed in the forensic literature (Fitzpatrick and Raven, 2012; Rawlins et al., 2006; Dawson and Hillier,2010) in comparing the inorganic composition of forensic samples with suspected crime scenes and alibi sites.

XRD patterns of control and test samples can be compared to determine if the soils are likely derived from the same location. If two soil samples have multiple similar mineral components, and particularly if the minerals are unusual in soils, the likelihood that they are sourced from the same location increases (Fitzpatrick, 2009).

Part II: Soil Material Transfer to Shoes

Part II of the study addresses the material transfer of soils from three sites in the District of Columbia to the soles of athletic shoes. Three pairs of shoes were used, each pair having a different tread distribution (Figures 16, 18). The three athletic shoes used were the Nike Air Pegasus, Reebok RealFlex, and Reebok Zignano (Figures 16, 17).

All shoes used in the study were US Women's size 8.5 and were worn by a 66 kg subject. At each location, for each pair of shoes, soil material was transferred to the shoes in two ways. First, the right shoe was worn and the subject walked at a pace of ~3 mph across the area selected for collecting the undisturbed soil samples; the area was approximately 60 feet in length (the left shoe was the subject's own and was not used in the study). The right shoe was then carefully removed from the foot and placed in a Ziploc ® bag. The subject then placed the left shoe used in the study on the left foot, replacing the shoe used for the right foot with her own, and jogged at a pace of 4.0-4.5 mph across the same area. This shoe was also then slowly removed from the foot and placed into a separate Ziploc® bag. This procedure was repeated for all three pairs of shoes during each soil transfer trial. An attempt was made to not retrace steps during the subsequent trials.

Figure 16 Left to right: Reebok RealFlex, Nike Air Pegasus, and Reebok Zignano sneakers, showing different tread patterns.

Figure 17 Left to right: Reebok RealFlex, Nike Air Pegasus, and Reebok Zignano shoes after soil transfer.

Reebok RealFlex shoes after a transfer at the Sherman Circle location. The ‘walking shoe’ (left image; right foot)

Nike Air Pegasus shoes after a transfer at Rock Creek Park. In both walking and jogging experiments, soil material had a tendency to accumulate on the shoe sole surface, with the larger particles becoming “trapped” in the treadgaps (refer to large gravel particle in right-foot shoe).

Reebok Zignano shoes after a trial at Rock Creek Park. The Zignanos consistently accumulated the least amount of soil material, which is attributed to the high percentage of tread gaps.

The measurement of shoe sole characteristics is critical in understanding the nature of soil transfer between the ground surface and shoes. Soil may transfer to the treads or the tread gaps of shoes, and it is important to relate soil transfer patterns to the characteristics of the shoes of interest. In this study, shoe treads are defined as the portion of the shoe sole which comes into contact with the ground with each step, and tread gaps are the concave portions in between the treads. Shoes have been a part or focus of several forensic studies (Chazottes et al., 2004; Croft and Pye, 2004a; Bull et al., 2006; Morgan et al., 2009); however, very little has been published about the characteristics of the sole of the shoes.

Shoe tread gap distributions were characterized by measuring the length of each tread gap on the shoe sole with a ruler, placing each measurement into 1-mm bins associated with the tread gap width. For each tread gap, the width was determined using the narrower dimension. These measurements were made for every tread gap across the shoe sole, yielding total linear length of each tread gap size bin (Figure 18, Appendix 11). This method of shoe sole characterization allows for the expression of differently-sized tread gaps as a percentage of total tread gap population. In this study, the tread gaps were measured with respect to the entire shoe sole area. Future studies may further this characterization by categorizing the tread gap distribution according to the front and back halves of the shoe. Different portions of the shoe sole may be in contact with the ground as velocity during transfer changes; for example, some people place more weight on the heel of the shoe during walking, but shift to the ball or toe portion of the shoe while jogging. This shift in area of the shoe in contact with the ground may result in different soil yields, and any differences of the shoe tread gap distributions between these areas may be an influencing factor in this process.

Figure 18 Tread gap measurement of the Nike Air Pegasus using a ruler. The narrower dimension (the width) of the tread gap is measured (orange arrow) allowing the tread gap to be assigned to a bin; then, the length of that tread gap is measured (blue arrow) and is used to compute the fraction of gap widths for a given shoe sole. This was repeated for every tread gap across the shoe sole. The end result was a total linear length of each size tread gap (increments of 1 mm) expressed as a percentage of total tread gap linear length.

The Reebok Zignano shoes contain tread gaps between 1 and 12 mm; the mean, median, and mode of tread gap distribution are 6.54 mm, 7 mm, and 7 mm (Figure 20). The Reebok Realflex shoes have tread gaps between 1 and 10 mm, with the mean, median, and mode are of smaller sizes, at 3.14 mm, 3 mm, and 2 mm, respectively. The Nike Air Pegasus shoes have a near-bimodal distribution, with the majority of the tread gaps between 1 and 6 mm. The >20 mm measurements are from the large concave structure in the heel, and are not present in the other two pairs of shoes. The mean and median for the Nike Air Pegasus are 3.47 mm and 4 mm. There are two modes for this pair of shoes, of 3 mm and 5 mm. These measurements did not include the measurements obtained from the large concave heel structure. During the course of this study, it was observed that the Nike Air Pegasus occassionally picked up large (1-3 cm) particles, in this heel structure whereas the other pairs of shoes did not. Particles larger than 1 cm were not included in the particle size distribution calculations.

ImageJ was used to create a “map” of the shoe soles and provide a means to quantify tread and tread gap percentage as a function of total shoe sole area. The procedure for characterizing the shoes in ImageJ involved photographing the individual shoes. The shoe soles were photographed with the camera lens parallel to the shoe sole (in order to minimize distortion) (Figure 16). The photographs were then imported to ImageJ. The outline of the shoe was traced and the total area of the shoe sole was calculated using the measure particle function (Figure 19, left images). Next, the individual contact surface areas (the treads) were traced on the original image and were measured (Figure 19, right images). The total areas of shoe “tread” and shoe “tread gap” were calculated by dividing the measured tread areas over the total shoe area for the respective shoe.

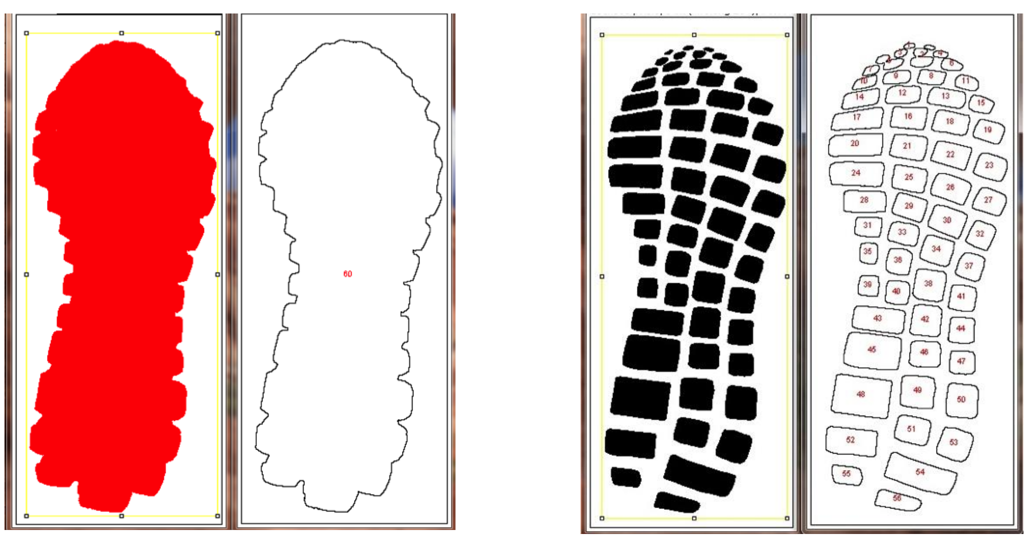


Figure 19 ImageJ sequence for characterizing shoe soles. Reebok RealFlex used in above example. Left: tracing the total shoe sole area. Right: tracing the treads.

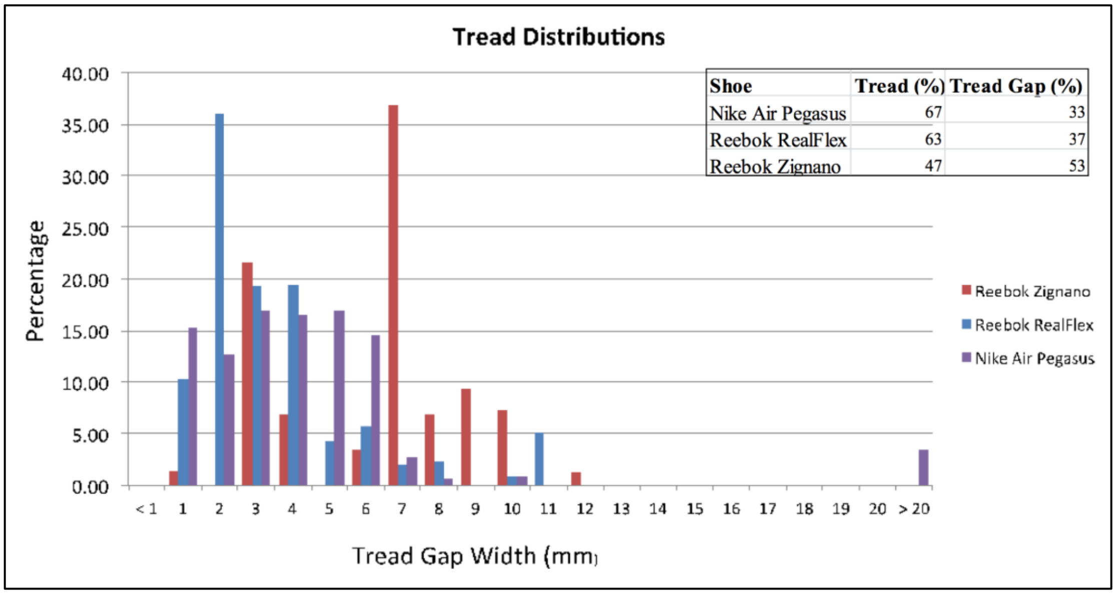


Figure 20 Tread distributions of the Reebok Zignano, Reebok RealFlex, and Nike Air Pegasus shoes. Distributions are expressed in percentage of each tread size (mm) measured across the shoe sole.

After accumulating soil material, the shoes were packed in sealed Ziploc© bags and taken back to the laboratory where they were characterized in the same manner as the undisturbed soil samples. The objectives of characterizing material accumulated on shoes were to 1) determine if and to what extent material transfer bias occurs as the shoes accumulate soil material from a location, and 2) determine how material property differences compare between shoe-ground interactions and also between shoes with different tread patterns.

Soil material was removed from the shoe soles in the laboratory by placing the shoe upright in the opened Ziploc© bag. The soles of the shoes were rinsed with distilled water while loosening and dislodging the sediment with a disposable wooden stirrer. After rinsing, the shoe was removed from the bag and placed sole-up on clean plastic film. The water-soil mixture that had collected at the bottom of the Ziploc© bag was then poured into a glass beaker. The Ziploc© bag was then rinsed with distilled water until all remaining soil residue had been rinsed from the bag. Upon visual inspection of the shoe, if there appeared to be any soil material still adhering to the shoe, the shoe was placed in another sealed Ziploc© bag with approximately 100 mL of distilled water with only the sole of the shoe in contact with the water. The bag was then placed in an ultrasonic bath for approximately 15 minutes. Any additional recovered sediment was then added to the glass beaker. This procedure was repeated until all sediment, upon visual inspection with the naked eye, was removed.

Chapter 5: Hypotheses

Hypothesis 1: There will be significant differences in undisturbed soil properties (soil color, particle size distribution) among sample locations. These differences may be due to geological location; Rock Creek Park is located in the Piedmont Province whereas Sherman Circle and Marvin Gaye Park are located on the Coastal Plain. Additionally, these differences may be due to soil collection location: proximity to the curb or street, the surrounding vegetation, or the slope at the location. Finally, these differences may be due to the soil being more of a natural soil (Rock Creek Park) or an urban soil (Marvin Gaye Park, Sherman Circle).

Hypothesis 2: There will be significant differences in both soil color and particle size distributions between the soils and the soil material recovered from shoes, and these differences will be a function of shoe tread size distribution. Additionally, the heavy mineral population will also aid in this discrimination.

Null Hypothesis: There will be no significant variation of the soil properties during an exchange of material between the shoes and the soil in place. Further, there will be no significant variation of these properties between samples from within the same site (i.e. between adjacent pedons).

Statistical tests were performed to determine if soil samples could be discriminated from each other at the 95% confidence level with respect to particle size distribution and color. Each data set will be subjected to an analysis of variance (ANOVA) or a t-test. The details of where and how these statistical analyses were used are given in Chapter 6.

Chapter 6: Results

Weather conditions were recorded for each shoe transfer experiment in order to determine whether soil transfer behavior could be attributed to soil moisture, season, time of day, or temperature. Table 2 contains weather condition information from the time of collection of samples, as well as soil moisture content for the transferred soil collections. In addition to focusing on the properties of the transferred soil, recording the amount of soil transferred to the shoe provides insight to soil transfer behavior according to shoe type. Table 3 lists soil accumulation data for the transfer portions of the study.

Soil Collection Conditions				
Location	Collection Date	Weather Conditions	Time of Collection	Soil Moisture (%)
RCP Bulk	06-14-2012	70°F; Sunny	Early Afternoon	
RCP Trial 1	09-06-2012	60°F; Light Rain	Early Afternoon	1.7
RCP Trial 2	12-01-2012	50°F; Sunny	Early Afternoon	3.1
RCP Trial 3	12-08-2012	45°F; Sunny	Afternoon	3.9
SHC Bulk	10-11-2011	50°F; Light Rain	Late Morning	
SHC Trial 1	10-13-2012	50°F; Cloudy	Late Morning	11.3
SHC Trial 2	12-18-2012	40°F; Cloudy	Early Afternoon	9.0
SHC Trial 3	12-27-2012	30°F; Sunny	Late Morning	8.9
MGP Bulk	07-26-2012	70°F; Overcast	Evening	
MGP Trial 1	11-29-2012	50°F; Clear	Evening	5.3
MGP Trial 2	01-03-2013	35°F; Clear	Evening	3.1
MGP Trial 3	01-10-2013	40°F; Clear	Evening	0.36

Table 2 Soil collection weather conditions and soil moisture content. RCP=Rock Creek Park; SHC=Sherman Circle; MGP=Marvin Gaye Park.

Location	Nike Walk	Nike Jog	RealFlex Walk	RealFlex Jog	Zignano Walk	Zignano Jog
Rock Creek Park 09-06-12	0.8149	0.2853	1.4745	0.2644	0.2701	0.6483
Rock Creek Park 12-01-12	1.1643	0.5134	1.3342	1.2579	0.1766	0.1087
Rock Creek Park 12-08-12	0.1910	0.2645	0.5938	0.7628	0.2075	0.0809
Sherman Circle 10-13-12	1.6278	1.4809	2.6428	1.6172	1.814	1.4832
Sherman Circle 12-18-12	6.6082	2.3763	5.9490	4.4796	5.3171	1.9633
Sherman Circle 12-27-12	1.0132	0.5901	2.8767	5.2953	1.0881	0.5497
Marvin Gaye Park 11-29-12	0.0759	0.1813	0.0376	0.0602	0.001	0.0193
Marvin Gaye Park 01-03-13	0.6970	0.2947	0.5008	0.2456	0.3846	0.1887
Marvin Gaye Park 01-10-13	0.5626	0.5969	0.6731	0.5620	0.5396	0.5712

Table 3 Weight of accumulated soil on shoes during the soil transfer portion of study. All weights are in grams. Highlighted samples reflect those that did not yield enough material to take soil color measurements. Samples were determined to not have enough material for color measurement if any portion of the white surface below the soil could be seen.

Soil moisture content (Table 2) was obtained by weighing soil samples pre- and post-drying in the oven. During each transfer experiment, an additional bulk soil sample was collected for the purpose of obtaining soil moisture content. The sample, of approximately 100 grams, was stored in a sealed hard Ziploc® 2" diameter circular container. Once back in the lab, this soil was promptly transferred to an empty beaker and then weighed. The soil was then oven-dried at 110º C overnight. The dried soil, still in the beaker, was then weighed. The difference between the weights provided the basis for the soil moisture content by means of weight percent.

Taking from the maximum ideal percentages of porosity (50%), and a water:soil density ratio of 1:2, the theoretical maximum percentage (by weight) of water in a soil is 25%. In this study, soil moisture ranged from 0.36% to 11.3%, all less than half of the theoretical maximum amount of soil moisture.

The Nike Air Pegasus and Reebok RealFlex shoes consistently accumulated more soil compared to the Reebok Zignano under all conditions (walking, jogging, soil moisture, season). This is likely due to 2 factors: the larger amount of tread (67% and 63% versus 47%) that makes up the shoe sole, and the higher percentage of smaller-sized tread gaps (Reebok Zignano tread gap mode is 7 mm versus 2 mm and 3 mm/5 mm for the Reebok RealFlex and Nike Air Pegasus). It was observed that larger particles in the soil ($\geq$ 1 cm) became trapped in the tread gap (Figure 17), and most of the finer fractions accumulated directly on the shoe tread. Approximately 67% of the Reebok Zignano's tread gaps are between 7 and 12 mm (Figure 20). This is in contrast to the Nike Air Pegasus, for which 90% of the tread gaps are between 1 mm and 6 mm, and the Reebok RealFlex distribution, for which 95% of the tread gaps are between 1 mm and 6 mm. The high percentage of larger tread gaps present in the Zignano shoes likely also contributed to the lower amount of soil material accumulating on the shoe. The transferred soil samples were debrided prior to obtaining initial reference weights.

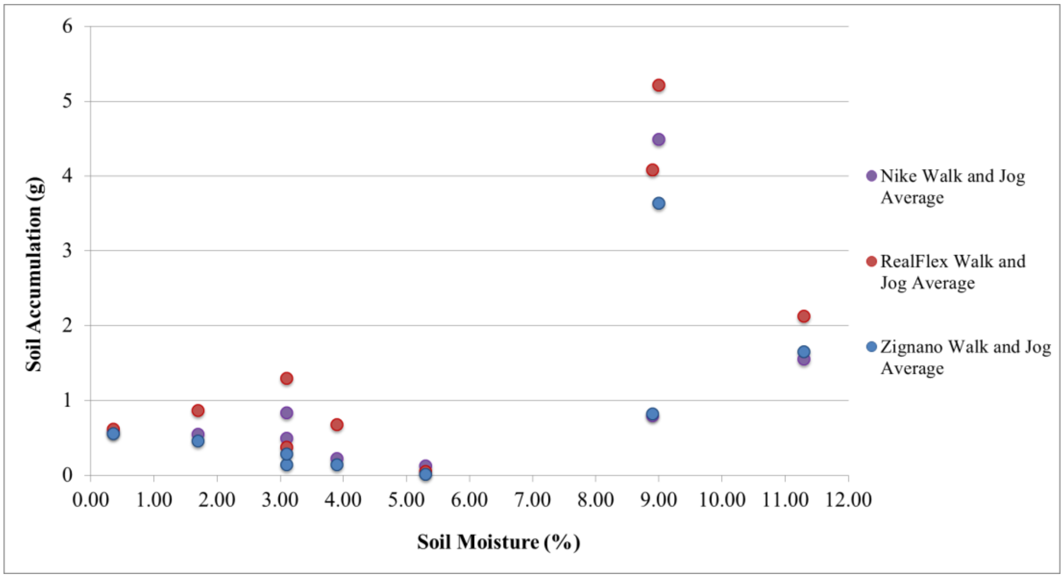


Figure 21 Soil accumulation onto the shoes as a function of soil moisture content. The "walk" and "jog" sample weights for each trial have been averaged. Soil accumulation plots with individual "walk" and "jog" transferred soil weights are given in Appendix 14.

The findings of this study regarding the relationship between soil accumulation on the shoe sole, and the distribution of treads and tread gaps, can be related to the nature of soil adhesion and the properties of the surface to which the soil is adhering. Soil adhesion comprises three factors: the soil, the solid surface to which the soil transfers, and the interface between soil and solid (Tong et al., 1994). The shoe sole-water interface, the formation of which will be a function of soil moisture content (Table 2), is important in soil adhesion mechanics (Tong et al., 1994). Soil adhesion to solid surfaces is low when the interface is dry; however, the adhesion force increases when water is present (increasing soil stickiness), either after absorbing water or containing a liquid water film (Tong et al., 1994). Following Locard's Exchange Principle, any surface that comes into contact with the ground has the potential to accumulate soil material. Shoes with larger percentages of exposed areas in contact with the ground surface (corresponding to a lower percentage of tread gap) have more surface area to which soil may adhere (Figure 21). Therefore, shoes with a larger percentage of surface area in contact with the ground are therefore more likely to have the potential to attract soil particles to them. As soil moisture increases, the soil may also become compacted within the tread gaps of shoes as its plasticity increases. Here, soil cohesion, rather than adhesion, is the dominant force associated with the soil transfer process. In addition to the aforementioned physical transfer processes, soil particles may also become electrostatically attracted to the shoe sole surface; this mechanism is dependent upon several factors, including ambient humidity, temperature, composition of the shoe sole, and mineralogy of the soil particle.

The physical properties of the shoe soles is also of critical importance in the soil adhesion system; rubber, the major component of many shoe soles, may lose its elasticity over time and become brittle. This brittleness may reduce soil adhesion potential, and the amount of soil material that transfers to the shoe would be reduced compared to a shoe sole that still contains the original elastic properties. The shoes used in this study were recently purchased shoes with no prior use; therefore, the effect of brittleness due to aging of the shoe sole is negligible.

However important water is in the soil adhesion process, it is not an absolute predictor of soil transfer behavior. For example, none of the soil samples collected during trials at Marvin Gaye Park yielded enough soil material to take color measurements from (Table 3), yet, the soil moisture contents during trials 1 and 2 (5.3% and 3.1%) were comparable to, or greater than, the soil moisture content of the Rock Creek Park soils (1.7% - 3.9%). Approximately half of the soil samples from Rock Creek Park did yield enough material to collect soil color measurements (Tables 2 and 3). During the Rock Creek Park and Sherman Circle transfers, the Reebok RealFlex consistently had the largest amount of soil transferred to it (Table 3), accumulating the most soil in 10 of the 12 combined transfers (walking and jogging for each of the three pairs of shoes). Further, in half of the transfers from these two locations, the order of soil accumulation amount, from largest to smallest, follows the order: Reebok RealFlex → Nike Air Pegasus → Reebok Zignano, indicating a positive correlation between tread surface area and soil accumulation. The Nike Air Pegasus dominated the Marvin Gaye Park transfers with respect to soil accumulation amounts, in 5 of the 6 transfers. In 67% of the transfers for Marvin Gaye Park, the order of soil accumulation, from largest to smallest, follows the order: Nike Air Pegasus → Reebok RealFlex → Reebok Zignano. Regardless of the properties of the accumulated soil, the consistency among the three locations lies in that the Reebok Zignano accumulated the least amount of soil material.

Particle Size Distribution

The results of the particle size distributions are given in Tables 4-6 below. Weights were determined by using a Mettler Toledo XP105 DeltaRange analytical balance. Soil weights were determined by using a 100 mL beaker as a tare. Uncertainty of the soil weight was calculated by incorporating the standard deviations of empty and full beaker weights into the individual measured weights of the samples. Both the empty and full beakers were weighed 10 times to obtain the standard deviation. The equations below were used to calculate error (ε), relative error (R.E.), and uncertainty (σ) of the soil sample (s).

Soil sample weight percent (s%) is calculated by dividing the mass of the individual size fraction by the initial whole soil weight (Σ individual size fraction mass). This calculation is the basis for the particle size distributions, with the uncertainty extending from this value.

(2) s % = (mass sample)/(Σ mass samples)

Error in the soil sample weight is calculated by taking the square root of the sum of the error of an empty beaker ($\varepsilon^2 B_e m$) and the error of a beaker filled with soil ($\varepsilon^2 B_f m$):

(3) $\varepsilon(s) = \sqrt{(\varepsilon^2 B_f m + \varepsilon^2 B_e m)}$

The error of the total sample mass (ε (Σ individual size fractions)) is calculated using a pooled standard deviation, taking into account the errors on the measurements of all four size fractions. These errors are assumed to be the same for each individual size fraction:

(4) $\varepsilon\,(\Sigma) = \sqrt{(\varepsilon^2 ms_1 + \varepsilon^2 ms_2 + \varepsilon^2 ms_3 + \varepsilon^2 ms_4)} = \sqrt{4} * \varepsilon^2 ms_1$

The Relative Error of the mass (R.E. mass) is obtained by dividing (2) by the average weight of the sample:

(5) R.E. mass (numerator) = $\varepsilon/x_{average}$

The Relative Error of the total sample mass (R.E. Σ mass) is calculated by taking the square root of (5) squared plus (4) squared. This incorporates the relative error of the mass and the error in the measurements of all four size fractions:

(6) R.E. Σ mass (denominator) = $\sqrt{((\text{R.E. mass}^2)+(\varepsilon(\Sigma)^2)}$

The total relative error is calculated by taking the square root of (5) squared plus (6) squared. This unitless value incorporates the relative errors into a pooled standard deviation:

(7) Total R.E.=$\sqrt{(\text{R.E. mass})^2+(\text{R.E. }\Sigma\text{ mass})^2}$

The absolute error (σ) applies the total relative error to the individual sample:

(8) σ = (Total R.E.)(mass of sample).

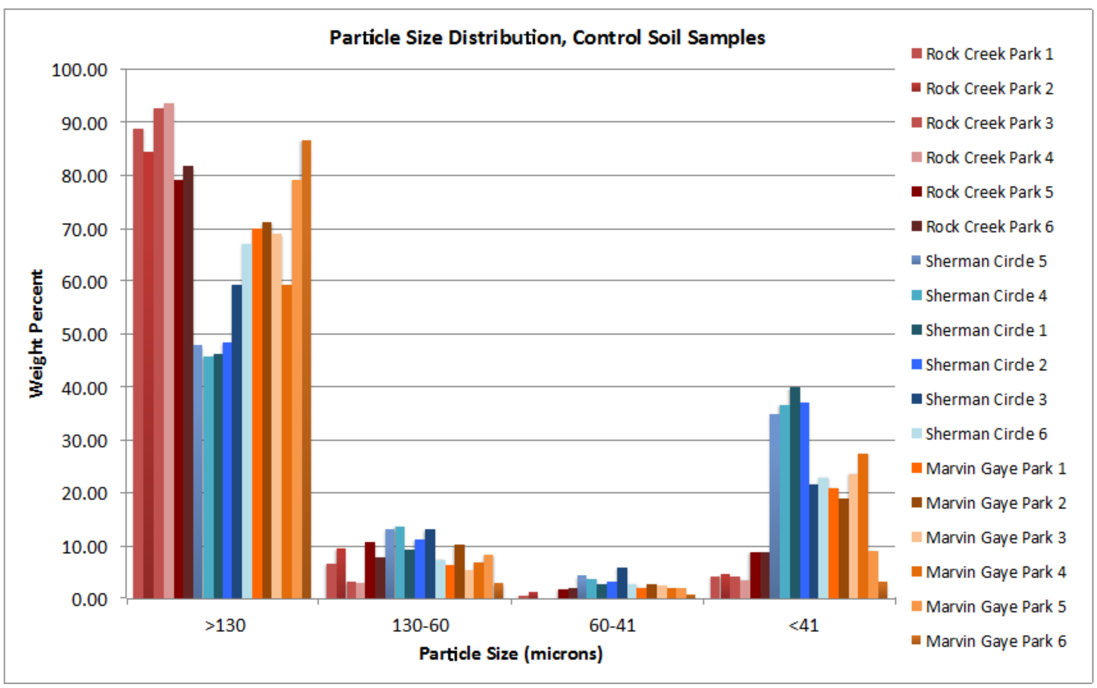


Figure 22 Histogram showing particle size distributions of the control soil samples. Each location had 6 samples collected to represent the soil from the area. The three locations are Rock Creek Park (red), Sherman Circle (blue), and Marvin Gaye Park (orange). Uncertainties in the weights are smaller than error bars can represent.

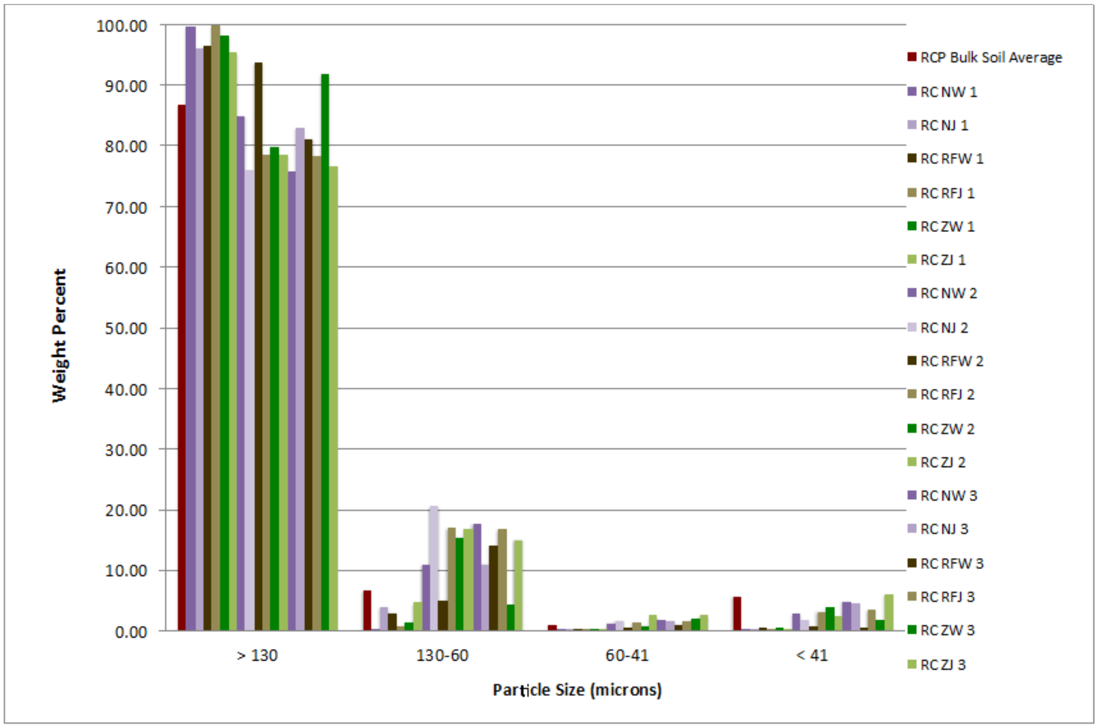


Figure 23 Histogram of the particle size distributions for Rock Creek Park (RCP) control soil compared to the transferred soil from that location. The red bar on the left of each size fraction represents the average of the values for the control soil sample (from Figure 22). Key: Nike Walk (NW); Nike Jog (NJ); RealFlex Walk (RFW); RealFlex Jog (RFJ); Zignano Walk (ZW) and Zignano Jog (ZJ) for transfers 1, 2, and 3.

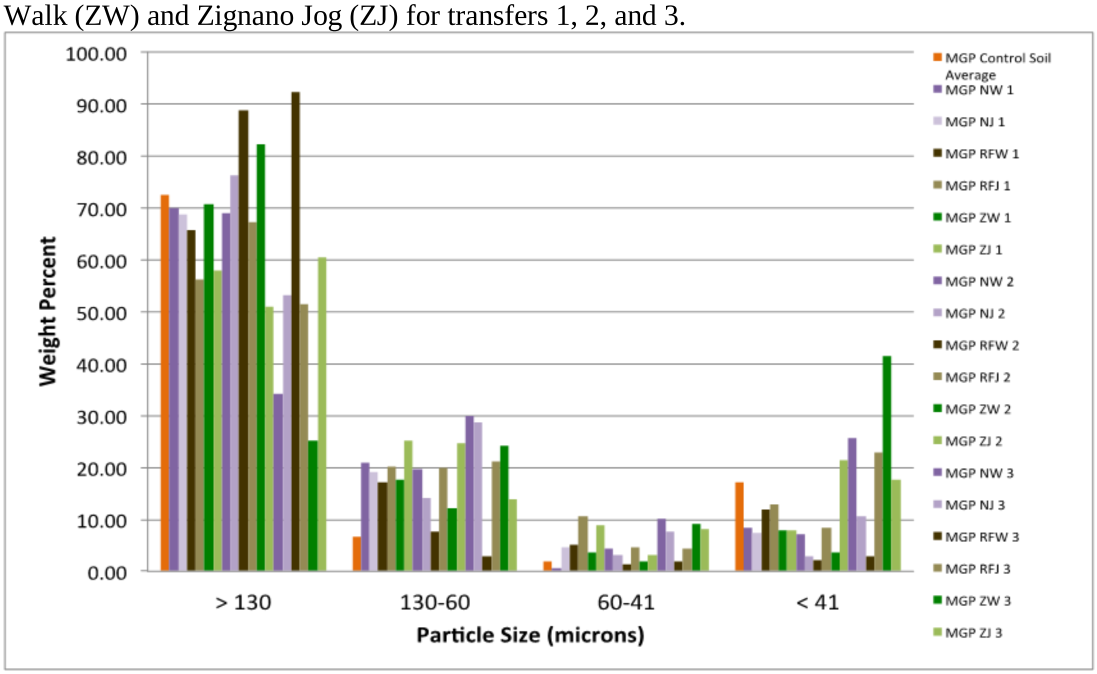


Figure 24 Histogram of the particle size distributions for Marvin Gaye Park Park (MGP) control soil compared to the transferred soil from that location. The orange bar on the left of each size fraction represents the average of the values for the control soil sample (from Figure 22). Key: Nike Walk (NW); Nike Jog (NJ); RealFlex Walk (RFW); RealFlex Jog (RFJ); Zignano Walk (ZW) and Zignano Jog (ZJ) for transfers 1, 2, and 3.

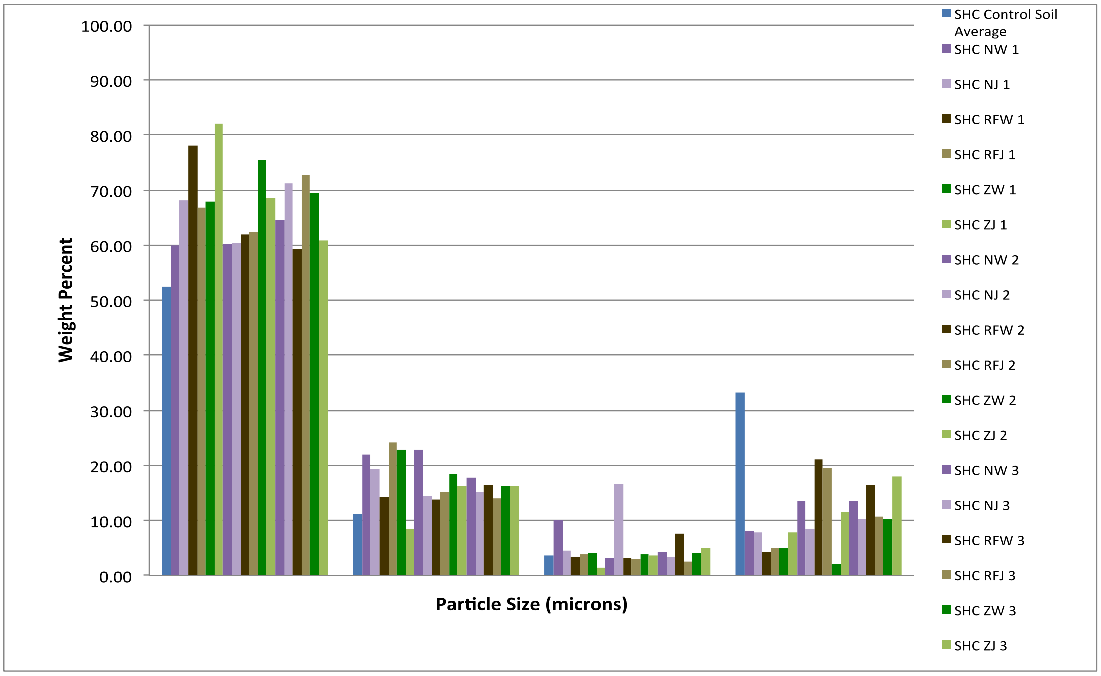


Figure 25 Histogram of the particle size distributions for Sherman Circle (SHC) control soil compared to the transferred soil from that location. The blue bar on the left of each size fraction represents the average of the values for the control soil sample (from Figure 22). Key: Nike Walk (NW); Nike Jog (NJ); RealFlex Walk (RFW); RealFlex Jog (RFJ); Zignano Walk (ZW) and Zignano Jog (ZJ) for transfers 1, 2, and 3.

Sample ID	> 130 Weight (g)	σ (g)	Percentage	130-60 Weight (g)	σ (g)	Percentage	60-41 Weight (g)	σ (g)	Percentage	< 41 Weight (g)	σ (g)	Percentage	Total Sample Weight (g)
RCP 1	75.50	0.0807	88.82	5.500	0.0059	6.471	0.5	0.0005	0.588	3.500	0.0037	4.118	85.00
RCP 2	62.00	0.0663	84.35	7.000	0.0075	9.524	1	0.0011	1.361	3.500	0.0037	4.762	73.50
RCP 3	89.00	0.0952	92.71	3.000	0.0032	3.125	0	0.0001	0.000	4.000	0.0043	4.167	96.00
RCP 4	93.50	0.0994	93.50	3.000	0.0032	3.000	0	0.0001	0.000	3.500	0.0037	3.500	100.0
RCP 5	45.00	0.0481	78.95	6.000	0.0064	10.53	1	0.0011	1.754	5.000	0.0053	8.772	57.00
RCP 6	42.00	0.0449	81.55	4.000	0.0043	7.767	1	0.0011	1.942	4.500	0.0048	8.738	51.50
RCP Bulk Soil Avg.	67.83		86.65	4.750		6.735	0.5833		0.9408	4.000		5.676	
Transfer 1 NW	14.1564	0.0151	99.75	0.0251	0.0001	0.177	0.0105	0.0001	0.0740	0.0001	0.0088	0.0007	14.192
Transfer 1 NJ	0.2421	0.0003	96.15	0.0097	0.0001	3.852	0.0001	0.0001	0.0397	0.0001	0.0088	0.0397	0.2518
Transfer 1 RFW	1.3670	0.0015	96.55	0.0422	0.0001	2.980	0.0006	0.0001	0.0424	0.0061	0.0088	0.4308	1.4159
Transfer 1 RFJ	0.2431	0.0003	99.92	0.0020	0.0001	0.822	0.0001	0.0001	0.0411	0.0001	0.0088	0.0411	0.2433
Transfer 1 ZW	0.2521	0.0003	98.13	0.0036	0.0001	1.401	0.0003	0.0001	0.1168	0.0009	0.0088	0.3503	0.2569
Transfer 1 ZJ	1.6700	0.0018	95.43	0.0799	0.0001	4.566	0.0006	0.0001	0.0343	0.0002	0.0088	0.0114	1.75
Average	2.9885		97.65	0.0271		2.300	0.0020		0.0580	0.0013		0.1457	3.0183
Transfer 2 NW	0.9494	0.0010	84.93	0.1224	0.0002	10.95	0.0141	0.0001	1.261	0.0319	0.0094	2.854	1.1178
Transfer 2 NJ	0.3484	0.0004	76.07	0.0941	0.0001	20.55	0.0074	0.0001	1.616	0.0081	0.0088	1.769	0.458
Transfer 2 RFW	1.202	0.0013	93.78	0.0642	0.0001	5.008	0.0063	0.0001	0.491	0.0093	0.0088	0.725	1.282
Transfer 2 RFJ	0.9487	0.0010	78.47	0.2053	0.0002	16.98	0.0166	0.0001	1.373	0.0384	0.0097	3.176	1.209
Trnasfer 2 ZW	0.1304	0.0003	79.85	0.0252	0.0001	15.43	0.0014	0.0001	0.857	0.0063	0.0088	3.858	0.1633
Transfer 2 ZJ	0.071	0.001	78.45	0.0152	0.0001	16.80	0.0022	0.0001	2.431	0.0021	0.0088	2.320	0.0905
Average	0.6084		81.93	0.0877		14.29	0.0080		1.338	0.0160		2.450	
Transfer 3 NW	0.1164	0.0002	75.73	0.0272	0.0001	17.70	0.0026	0.0001	1.692	0.0075	0.0088	4.880	0.1537
Transfer 3 NJ	0.2139	0.0002	82.87	0.0284	0.0001	11.00	0.0042	0.0001	1.627	0.0116	0.0088	4.494	0.2581
Transfer 3 RFW	0.4512	0.0005	81.19	0.0778	0.0001	14.00	0.0057	0.0001	1.026	0.0021	0.0090	0.378	0.5557
Transfer 3 RFJ	0.5504	0.0006	78.29	0.1178	0.0002	16.76	0.0107	0.0001	1.522	0.0241	0.0091	3.428	0.703
Transfer 3 ZW	0.1751	0.0002	91.92	0.0081	0.0001	4.252	0.0038	0.0001	1.995	0.0035	0.0088	1.837	0.1905
Transfer 3 ZJ	0.0453	0.0001	76.52	0.0089	0.0001	15.03	0.0015	0.0001	2.534	0.0035	0.0088	5.912	0.0592
Average	0.2587		81.09	0.0447		13.12	0.0048		1.733	0.0087		3.488	

Table 4 Weights of particle size fractions for samples from Rock Creek Park. NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog. Uncertainties (1σ) were calculated using equations 2-8, and are in grams. Percentage is equal to the weight of the size fraction divided by the weight of the total sample for a given transfer exercise.

Sample ID	> 130 Weight (g)	σ (g)	Percentage	130-60 Weight (g)	σ (g)	Percentage	60-41 Weight (g)	σ (g)	Percentage	< 41 Weight (g)	σ (g)	Percentage	Total Sample Weight (g)
MGP 1	27.30	0.0292	69.99	2.445	0.0026	6.269	0.8177	0.0009	2.097	8.180	0.0087	20.97	39.00
MGP 2	19.87	0.0212	71.22	2.849	0.0031	10.21	0.7339	0.0008	2.630	5.272	0.0056	18.89	27.90
MGP 3	23.12	0.0247	69.00	1.784	0.0019	5.327	0.8007	0.0009	2.390	7.919	0.0085	23.64	33.50
MGP 4	17.77	0.0190	59.35	2.060	0.0022	6.860	0.5765	0.0006	1.930	8.198	0.0088	27.38	29.94
MGP 5	26.83	0.0287	79.10	2.790	0.0030	8.230	0.6589	0.0007	1.940	3.008	0.0032	8.870	33.92
MGP 6	23.48	0.0251	86.64	0.812	0.0009	3.000	0.1885	0.0002	0.700	0.848	0.0008	3.130	27.10
MGP Bulk Soil Average	23.06		72.55	2.123		6.650	0.6294		1.948	5.571		17.15	31.89
Transfer1 NW	0.0381	0.0001	69.91	0.0114	0.0001	20.92	0.0004	0.0001	0.7339	0.0046	0.0001	8.440	0.0545
Transfer 1 NJ	0.0266	0.0001	68.73	0.0074	0.0001	19.12	0.0018	0.0001	4.651	0.0029	0.0001	7.494	0.0387
Transfer 1 RFW	0.0278	0.0001	65.72	0.0073	0.0001	17.26	0.0022	0.0001	5.201	0.0050	0.0001	11.82	0.0423
Transfer 1 RFJ	0.0304	0.0001	56.19	0.0109	0.0001	20.15	0.0058	0.0001	10.72	0.0070	0.0001	12.94	0.0541
Transfer 1 ZW	0.0136	0.0001	70.83	0.0034	0.0001	17.71	0.0007	0.0001	3.646	0.0015	0.0001	7.813	0.0192
Transfer 1 ZJ	0.0097	0.0001	58.08	0.0042	0.0001	25.15	0.0015	0.0001	8.982	0.0013	0.0001	7.784	0.0167
Average	0.0244		64.91	0.0074		20.05	0.0021		5.656	0.0037		9.382	0.0376
Transfer 2 NW	0.4553	0.0005	68.89	0.1291	0.0002	19.53	0.0289	0.0001	4.373	0.048	0.0001	7.202	0.6609
Transfer 2 NJ	0.209	0.0002	76.36	0.0384	0.0001	14.03	0.0083	0.0001	3.033	0.008	0.0001	2.923	0.2737
Transfer 2 RFW	0.4107	0.0004	88.72	0.0356	0.0001	7.691	0.0065	0.0001	1.404	0.010	0.0001	2.182	0.4629
Transfer 2 RFJ	0.1461	0.0002	67.20	0.0431	0.0001	19.83	0.0099	0.0001	4.554	0.018	0.0001	8.418	0.2174
Transfer 2 ZW	0.3015	0.0003	82.31	0.0446	0.0001	12.18	0.0067	0.0001	1.829	0.0135	0.0001	3.686	0.3663
Transfer 2 ZJ	0.0970	0.0001	50.87	0.0468	0.0001	24.54	0.0061	0.0001	3.199	0.0408	0.0001	21.39	0.1907
Average	0.2699		72.39	0.0563		16.30	0.0111		3.065	0.0231		7.634	
Transfer 3 NW	0.0114	0.0001	34.13	0.0100	0.0001	29.94	0.0034	0.0001	10.18	0.0086	0.0001	25.75	0.0334
Transfer 3 NJ	0.0364	0.0001	53.22	0.0196	0.0001	28.65	0.0052	0.0001	7.602	0.0072	0.0001	10.53	0.0684
Transfer 3 RFW	0.1309	0.0002	92.38	0.0040	0.0001	2.823	0.0026	0.0001	1.835	0.0042	0.0001	2.964	0.1417
Transfer 3 RFJ	0.0188	0.0001	51.51	0.0077	0.0001	21.10	0.0016	0.0001	4.3836	0.0084	0.0001	23.01	0.0365
Transfer 3 ZW	0.0025	0.0001	25.25	0.0024	0.0001	24.24	0.0009	0.0001	9.0909	0.0041	0.0001	41.41	0.0099
Transfer 3 ZJ	0.0276	0.0001	60.39	0.0063	0.0001	13.79	0.0037	0.0001	8.0963	0.0081	0.0001	17.72	0.0457
Average	0.0379		52.81	0.0083		20.09	0.0029		6.8646	0.0068		20.23	

Table 5 Weights of particle size fractions for samples from Marvin Gaye Park. NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog. Uncertainties (σ) were calculated using equation 8, and are in grams.

Sample ID	> 130 Weight (g)	σ (g)	Percentage	130-60 Weight (g)	σ (g)	Percentage	60-41 Weight (g)	σ (g)	Percentage	< 41 Weight (g)	σ (g)	Percentage	Total Sample Weight (g)
SHC 1	25.50	0.0274	46.43	5.000	0.0054	9.100	1.500	0.0016	2.73	22.00	0.0393	46.40	54.00
SHC 2	30.25	0.0325	48.40	7.000	0.0075	11.20	2.000	0.0022	3.20	23.25	0.0250	37.20	62.50
SHC 3	20.50	0.0221	59.42	4.500	0.0043	13.04	2.000	0.0022	5.80	7.500	0.0081	21.45	34.50
SHC 4	25.00	0.0265	45.87	7.500	0.0081	13.76	2.000	0.0022	3.67	20.00	0.0215	36.70	54.50
SHC 5	22.00	0.0237	47.83	6.000	0.0065	13.04	2.000	0.0022	4.35	16.00	0.0172	34.78	46.00
SHC 6	36.50	0.0393	66.97	4.000	0.0043	7.340	1.500	0.0016	2.75	12.50	0.0134	22.94	54.50
SH Bulk Average	26.63		52.49	5.667		11.25	1.833		3.75	16.88		33.25	
Transfer1 NW	0.9306	0.001	59.97	0.3396	0.0004	21.88	0.1552	0.0002	10.00	0.1264	0.0002	8.145	1.552
Transfer 1 NJ	0.9048	0.001	68.04	0.2574	0.0003	19.35	0.0609	0.0001	4.579	0.1032	0.0001	7.760	1.330
Transfer 1 RFW	2.006	0.0021	78.00	0.3688	0.0004	14.34	0.0883	0.0001	3.434	0.1087	0.0001	4.227	2.571
Transfer 1 RFJ	1.021	0.0011	66.86	0.3705	0.0004	24.26	0.0588	0.0001	3.851	0.0768	0.0001	5.029	1.527
Transfer 1 ZW	1.185	0.0013	67.94	0.4002	0.0004	22.94	0.0715	0.0001	4.098	0.0877	0.0001	5.027	1.745
Transfer 1 ZJ	1.237	0.0013	81.99	0.1293	0.0002	8.573	0.023	0.0001	1.525	0.1194	0.0002	7.916	1.508
Average	1.214		70.46	0.3110		18.56	0.0763		4.581	0.1037		6.351	1.705
Transfer 2 NW	1.526	0.0016	60.19	0.5819	0.0003	22.95	0.0821	0.0001	3.239	0.3451	0.0004	13.61	2.535
Transfer 2 NJ	1.601	0.0017	60.46	0.3813	0.0006	14.40	0.4413	0.0005	16.67	0.2242	0.0003	8.468	2.648
Transfer 2 RFW	3.560	0.0038	61.91	0.7913	0.0004	13.76	0.1825	0.0002	3.174	1.2168	0.0013	21.16	5.751
Transfer 2 RFJ	2.963	0.0032	62.44	0.7181	0.0009	15.13	0.1381	0.0002	2.911	0.9259	0.001	19.51	4.745
Transfer 2 ZW	3.160	0.0034	75.47	0.7760	0.0008	18.54	0.1608	0.0002	3.841	0.09	0.0001	2.150	4.186
Transfer 2 ZJ	1.320	0.0014	68.66	0.3104	0.0008	16.15	0.0696	0.0001	3.621	0.2224	0.0003	11.57	1.922
Average	2.355		64.86	0.5932		16.82	0.1791		5.576	0.5041		12.75	3.631
Transfer 3 NW	0.6218	0.0007	64.53	0.1704	0.0003	17.68	0.0414	0.0001	4.296	0.1300	0.0002	13.49	0.9636
Transfer 3 NJ	0.3976	0.0004	71.20	0.0849	0.0002	15.20	0.0191	0.0001	3.420	0.0568	0.0001	10.17	0.5584
Transfer 3 RFW	1.750	0.0019	59.35	0.4867	0.0001	16.51	0.2276	0.0003	7.718	0.4845	0.0005	16.43	2.949
Transfer 3 RFJ	3.798	0.0041	72.68	0.7356	0.0005	14.08	0.136	0.0002	2.602	0.5562	0.0006	10.64	5.226
Transfer 3 ZW	0.7265	0.0008	69.49	0.1687	0.0008	16.14	0.0435	0.0001	4.161	0.1068	0.0001	10.22	1.046
Transfer 3 ZJ	0.3179	0.0004	60.77	0.0854	0.0002	16.33	0.026	0.0001	4.970	0.0938	0.0001	17.93	0.5231
Average	1.269		66.34	0.2886		15.99	0.0823		4.528	0.2380		13.15	1.878

Table 6 Weights of particle size fractions for samples from Sherman Circle. NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog. Uncertainties (σ) were calculated using equation 8, and are in grams.

A single sample t-test was performed to determine whether the particle size distributions of transferred soil material differed significantly from the undisturbed soil material (Tables 8-10). The data to which the t-tests are applied are expressed as weight percent of the respective grain size fractions of an undisturbed or transferred soil sample. The single sample t-test is used to determine whether a sample comes from a particular population, when the data on the population of one of the samples is not available. The single sample t-test compares a single measurement with the sample mean of another set of samples and tests whether the single measurement (from the transferred soil) is part of the larger population for which an estimate of both the mean and standard deviation exists (the undisturbed soil). In forensic investigations, scientists are not afforded the luxury of characterizing multiple samples to obtain the full population information in comparison or provenance analyses (i.e. n=1), and therefore the single sample t-test is appropriate for this study. The t-statistic has a single critical value for any given significance level regardless of sample size, with the critical value dependent upon the number of degrees of freedom.

The formula for determining the single sample t-statistic is:

(9) $t= |(\mu - x)| / \sqrt{(\sigma^2/n)}$

where μ is sample mean of the weight percent of a given grain size of the undisturbed soil, x is weight percent of a given grain size of the transferred soil sample, σ is the standard deviation for the undisturbed soil population, and n represent the number of measurements used in determining the standard deviation (n=6). In what follows, the term “t-test” indicates the single sample t-test.

The critical t-value is determined from the number of degrees of freedom, which is given by n-1. In this study, the degrees of freedom (DF) was calculated by accounting for the 6 samples collected for the undisturbed soil, yielding DF = 5. Using a 2-tailed t-test at the 95% confidence level, the corresponding critical t-value for these samples is 2.5706. Comparing the particle size distributions between the transferred soil samples and the undisturbed soil samples, if a calculated t-statistic is greater than 2.5706, then the two distributions are significantly different. Values greater than the t-statistic, representing transferred soil particle size percentages statistically different from the undisturbed soil sample, are highlighted in Tables 8-10.

Inter-site variation in the particle size distributions of the undisturbed soil is given in Table 7. There is a statistical difference in 94% of the particle size distribution comparisons between any two or among all three locations (Table 7). The only two samples that did not exhibit a significant difference were Rock Creek Park-Marvin Gaye Park (RCP-MGP) in the 130-60 μm fraction. Between Rock Creek Park and Sherman Circle (RCP-SHC), the largest differences (highest F statistic value) lie in the end member size fractions, >130 μm and < 41 μm. These differences also happen to be the largest differences of all comparisons between any two locations and among all three locations. Between Rock Creek Park and Marvin Gaye Park, the largest differences are also in the end member size fractions. Between Sherman Circle and Marvin Gaye Park undisturbed soils, the largest difference was in the >130 μm fraction. The smallest difference in particle size distribution of the undisturbed soils between or among locations was usually seen in the 130-60 μm size fraction.

Undisturbed Soil Particle Size Distribution Comparison: Inter-site Variation				
	F statistic >130	**F statistic 130-60**	**F statistic 60-41**	**F statistic < 41**
RCP-SHC	63.010	7.3700	22.240	47.750
RCP-MGP	9.6900	0.0027	5.0900	8.6100
SHC-MGP	14.850	10.050	10.640	8.8600
F critical	**3.2850**			
RCP-SHC-MGP	26.730	5.4900	14.150	19.030
F critical	**2.6952**	**two-tailed 95% CI**		

Table 7 Inter-site variation in particle size distributions of the undisturbed soil for Rock Creek Park (RCP), Sherman Circle (SHC), and Marvin Gaye Park (MGP). Each F statistic was calculated for each size fraction comparison by ANOVA. Samples with an F statistic larger than the critical value, indicating a significant difference, are highlighted.

Rock Creek Park				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	5.3646	5.067	2.4569	5.749
Transfer 1 NJ	3.8900	2.227	2.5540	5.709
Transfer 1 RFW	4.0532	2.901	2.5464	5.313
Transfer 1 RFJ	5.4337	4.568	2.5501	5.708
Transfer 1 ZW	4.7023	4.121	2.3356	5.395
Transfer 1 ZJ	3.5955	1.676	2.5694	5.738
Transfer 2 NW	0.7014	3.256	0.9086	2.859
Transfer 2 NJ	4.3313	10.669	1.9129	3.958
Transfer 2 RFW	2.9185	1.335	1.2737	5.015
Transfer 2 RFJ	3.3486	7.915	1.2250	2.532
Trnasfer 2 ZW	2.7822	6.718	0.2367	1.842
Transfer 2 ZJ	3.3555	7.772	4.2234	3.399
Transfer 3 NW	4.4697	8.468	2.1279	0.807
Transfer 3 NJ	1.5449	3.297	1.9456	1.197
Transfer 3 RFW	2.2328	5.612	0.2407	5.367
Transfer 3 RFJ	3.4210	7.742	1.6474	2.277
Transfer 3 ZW	2.1572	1.919	2.9871	3.889
Transfer 3 ZJ	4.1469	6.411	4.5149	0.239
t critical	**2.5706**	**two-tailed 95% CI**		

Table 8 Rock Creek Park particle size distribution t-test results. A single-sample t-test was performed for each shoe transfer and the individual size fractions of the respective undisturbed soil to look for significant differences in particle size as a result of the soil transfer process. NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog.

Marvin Gaye Park				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	0.69229	14.16161	4.44131	2.30117
Transfer 1 NJ	1.00013	12.37899	9.89024	2.55140
Transfer 1 RFW	1.78988	10.52909	11.90168	1.40790
Transfer 1 RFJ	4.28765	13.39778	32.09697	1.11225
Transfer 1 ZW	0.44980	10.97639	6.21214	2.46710
Transfer 1 ZJ	3.79181	18.36240	25.73520	2.47452
Transfer 2 NW	0.95896	12.78844	8.87191	2.62837
Transfer 2 NJ	0.99916	7.32538	3.96826	3.75934
Transfer 2 RFW	4.23967	1.03322	1.98914	3.95518
Transfer 2 RFJ	1.40133	13.07751	9.53410	2.30717
Trnasfer 2 ZW	2.55846	5.48502	0.43456	3.55780
Transfer 2 ZJ	5.68401	17.75839	4.57641	1.12249
Transfer 3 NW	10.07035	23.11718	30.11676	2.27309
Transfer 3 NJ	5.06771	21.84159	20.68743	1.74989
Transfer 3 RFW	5.19775	3.79835	0.41349	3.74848
Transfer 3 RFJ	5.51583	14.33874	8.91120	1.55032
Transfer 3 ZW	12.39785	17.46187	26.13352	6.41326
Transfer 3 ZJ	3.18628	7.08279	22.49457	0.15242
tcritical	**2.5706**	**two-tailed 95% CI**		

Table 9 Sherman Circle particle size distribution t-test results. A single-sample t-test was performed for each shoe transfer and the individual size fractions of the respective undisturbed soil to look for significant differences in particle size as a result of the soil transfer process.NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog.

Sherman Circle				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	2.11	10.201	13.024	6.493
Transfer 1 NJ	4.39	7.776	1.728	6.593
Transfer 1 RFW	7.20	2.969	0.658	7.506
Transfer 1 RFJ	4.06	12.483	0.210	7.299
Transfer 1 ZW	4.36	11.213	0.726	7.300
Transfer 1 ZJ	8.33	2.564	4.636	6.552
Transfer 2 NW	2.18	11.227	1.066	5.079
Transfer 2 NJ	2.25	3.026	26.914	6.409
Transfer 2 RFW	2.66	2.411	1.201	3.126
Transfer 2 RFJ	2.81	3.728	1.749	3.552
Trnasfer 2 ZW	6.49	6.991	0.190	8.044
Transfer 2 ZJ	4.56	4.701	0.269	5.607
Transfer 3 NW	3.40	6.173	1.138	5.110
Transfer 3 NJ	5.28	3.795	0.686	5.969
Transfer 3 RFW	1.94	5.043	8.268	4.350
Transfer 3 RFJ	5.70	2.713	2.391	5.847
Transfer 3 ZW	4.80	4.689	0.856	5.958
Transfer 3 ZJ	2.34	4.871	2.542	3.961
t critical	**2.5706**	**two-tailed 95% CI**		

Table 10 Marvin Gaye Park particle size distribution t-test results. A single-sample t-test was performed for each shoe transfer and the individual size fractions of the respective undisturbed soil to look for significant differences in particle size as a result of the soil transfer process. NW=Nike Walk; NJ=Nike Jog; RFW=RealFlex Walk; RFJ=RealFlex Jog; ZW=Zignano Walk; ZJ=Zignano Jog.

The following sections describe the behavior of the transferred soil compared to the undisturbed soil, and whether any trends could be established according to soil moisture content, shoe style, or walking versus jogging, and as a function of particle size distribution.

Rock Creek Park

The size fraction that is greater than 130 microns appears to be sensitive to soil moisture content, with increasing soil moisture corresponding to a better match between the transferred soil and the undisturbed soil (Figure 26). Soil moisture was 1.7% at the time transfer 1 took place; these samples are all more enriched in the >130 micron size fraction compared to the undisturbed soil (Table 8). During transfer 2, the soil moisture was nearly twice the amount of transfer 1, at 3.1%, where the only shoe to pass the t-test was the Nike Air Pegasus Walk (NW2). Interestingly, 4 of the 5 statistically different transferred soil samples at this transfer had a lower percentage of this size fraction compared to the undisturbed soil. During transfer 3, with the highest measured soil moisture (3.9%), 3 of the 6 shoes pass the t-test: Nike Air Pegasus Jog (NJ3), RealFlex Walk (RFW3), and Zignano Walk (ZW3). In contrast to transfer 1, except for RealFlex Walk 2 (RFW2), the samples from transfers 2 and 3 that did not pass the t-test had a lower percentage of this size fraction in comparison to the undisturbed soil (Table 8). These results suggest that the fractionation of the >130 micron size fraction is sensitive to soil moisture, with lower soil moisture corresponding to more of these particles transferring. The data also suggests that increasing soil moisture increases the likelihood of obtaining particle size distribution results matching the undisturbed soil sample, though further study is required to study the effects of soil moisture on the soil transfer process.

The 130-60 micron size fraction does not appear to be sensitive to soil moisture, shoe style, or walking/jogging. During transfer 1, only two samples passed the t-test: the Nike Air Pegasus Jog (NJ1) and Zignano Jog (ZJ1). For transfers 2 and 3, the only samples to pass the t-test were RealFlex Walk (RFW2) and Zignano Walk (ZW3), respectively. All other samples failed the t-test, meaning the percentage of this size fraction of the transferred soil is significantly different from the percentage obtained from the undisturbed soil samples. Interestingly, the relationship between enrichment and depletion of this size fraction is inverse to the >130 micron fraction; all failed samples from transfer 1 are depleted in the 130-60 micron size fraction, whereas the failed soil samples from transfers 2 and 3 have a higher percentage of this size fraction in comparison to the undisturbed soil samples (Figure 27). The different soil moisture contents between transfer 1 and transfers 2 and 3 may be the cause of the enrichments and depletions, but all transfers had a majority of the samples fail the t-test (Table 8). The data suggests that this size fraction is consistently affected by the soil transfer process regardless of soil moisture, and should not be used in forensic analyses to compare the particle size distribution of soil samples.

The 60-41 micron size fraction appears to be the least sensitive to soil moisture and walking versus jogging. Among the three transfers, only three samples (17%) did *not* pass the t-test: Zignano Jog 2 (ZJ2), Zignano Walk 3 (ZW3), and Zignano Jog 3 (ZJ3). The results suggest that this size fraction may be sensitive to shoe tread gap distribution, especially with increasing soil moisture, but this would need to be studied further to be confirmed. All three transferred soil sampled that showed to be different from the undisturbed soil sample had an enrichment of this size fraction (a higher percentage of the 60-41 micron fraction compared to the undisturbed soil samples) (Figure 28). This size fraction is the most appropriate to use in particle size distribution comparisons due to the resistance of influence by soil moisture content and walking versus jogging.

The < 41 micron size fraction does appear to be sensitive to soil moisture content, but not shoe style or walking versus jogging. All samples from transfer 1 (with soil moisture 1.7%) fail the t-test; as soil moisture increased to 3.1% for transfer 2, two samples did show similarity to the undisturbed soil sample: RealFlex Jog (RFJ2) and Zignano Walk (ZW2). The samples that failed the t-test for this transfer were all depleted in this size fraction compared to the undisturbed soil. Transfer 3, with the highest soil moisture (3.9%) had the largest amount of samples show similarity to the undisturbed soil sample (4 of the 6). The samples that did not pass were the RealFlex Walk (RFW3) and Zignano Walk (ZW3), which, similar to transfer 2, were also depleted in this size fraction compared to the undisturbed soil (Figure 29).

These results indicate that the two end member size fractions (>130 microns and <41 microns) are affected by the soil moisture content at the time of transfer, but the two middle fractions (130-60 microns and 60-41 microns) are not. None of the size fractions have a strong indication of influence by walking versus jogging or shoe style.

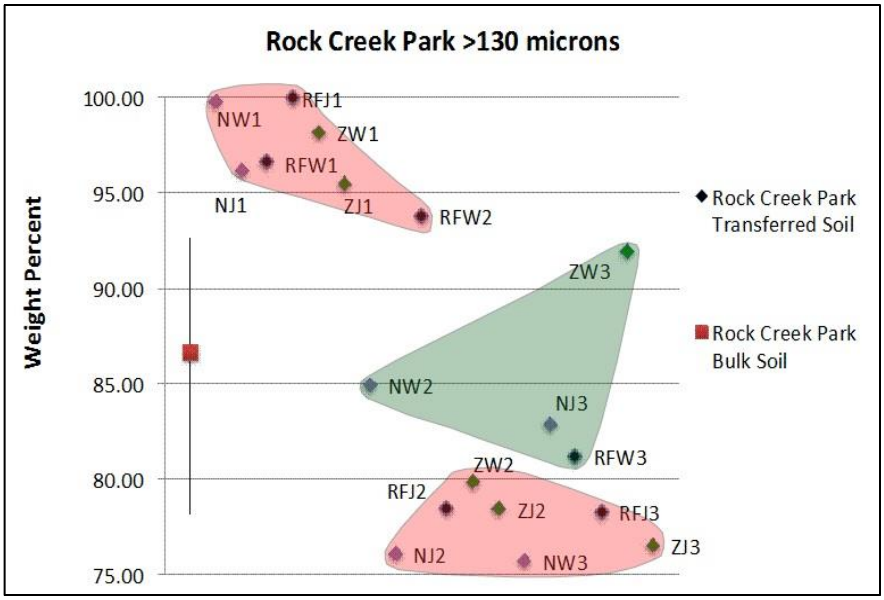


Figure 26 This scatter plot shows how the relative weight percent of the transferred soil (diamonds) compare to the undisturbed soil (red square) for the Rock Creek Park >130 micron size fraction. The square data point represents the average weight percent of the undisturbed soil sample for the specified size fraction, with the lines extending from it showing the range of weight percent measured of all 6 undisturbed soil samples from that location. The lines do not represent uncertainty. The red and green clusters were hand drawn and are meant to capture the transferred soil samples that, compared to the undisturbed soil, fail and pass the t-rest, respectively. There is no statistical significance to the shape of these clusters. These explanations apply to Figures 26-37.

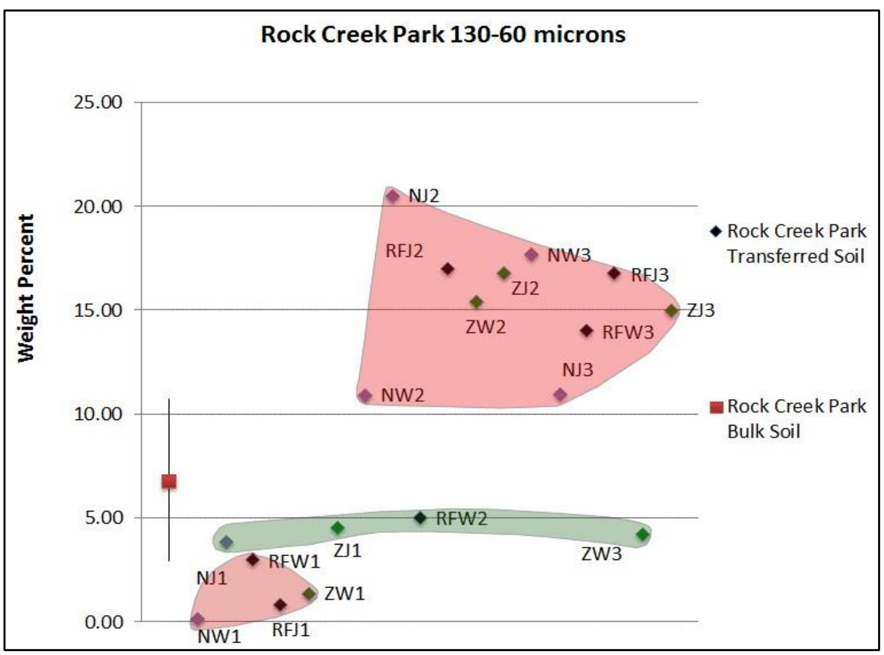


Figure 27 Relative weight percent for the Rock Creek Park transferred soil (diamonds) compared to the undisturbed soil (red square) for the 130-60 micron size fraction.

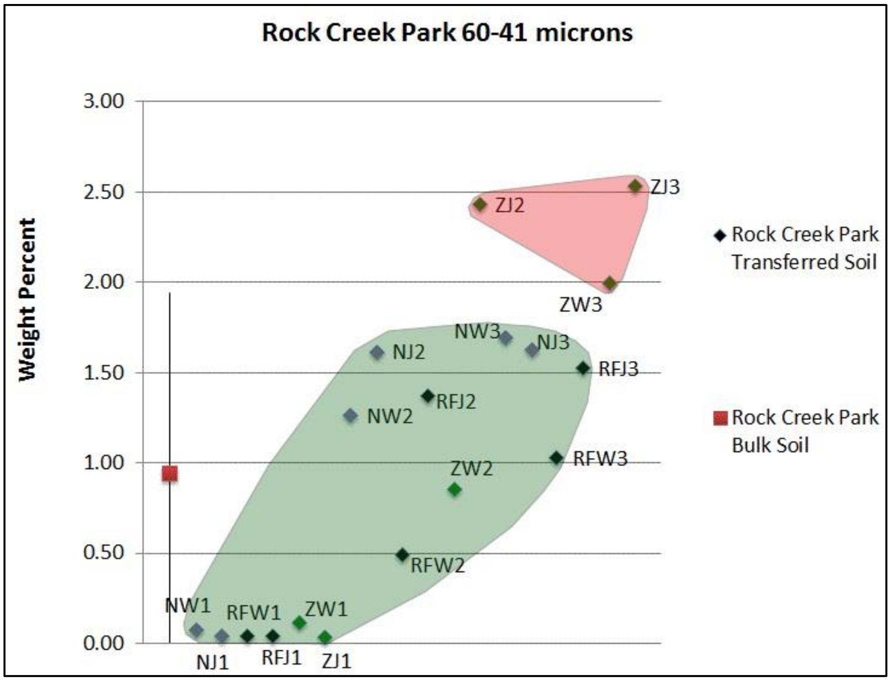


Figure 28 Relative weight percent for the Rock Creek Park transferred soil (diamonds) compared to the undisturbed soil (red square) for the 60-41 micron size fraction.

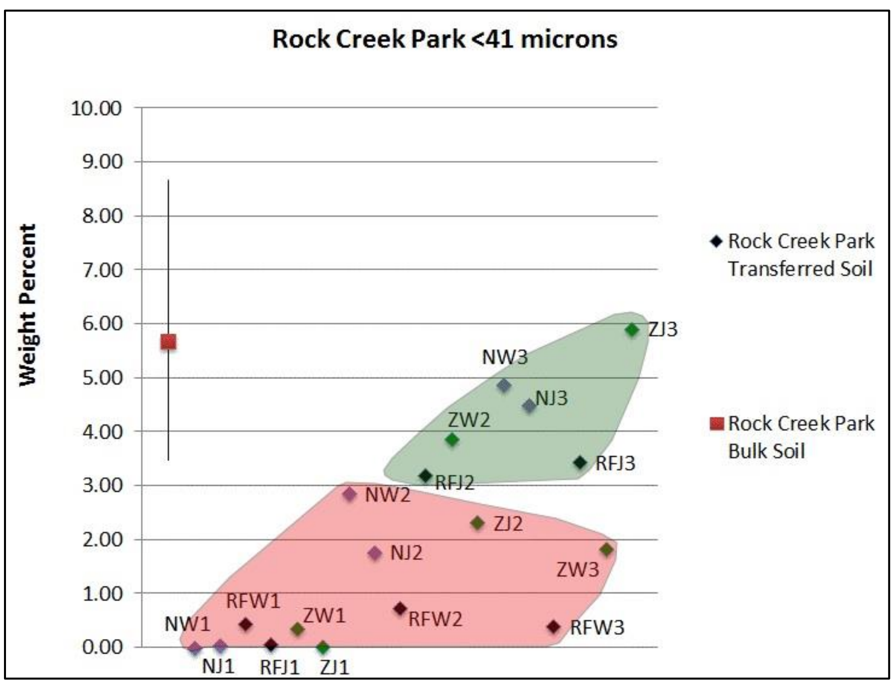


Figure 29 Relative weight percent for the Rock Creek Park transferred soil (diamonds) compared to the undisturbed soil (red square) for the < 41 micron size fraction.

Sherman Circle

The transferred soil samples in the >130 micron size fraction are consistently different from the undisturbed soil, with no clear trend according to soil moisture, shoe style, or walking versus jogging. Few samples passed the t-test: Nike Air Pegasus Walk 1 (NW1), Nike Air Pegasus Walk and Jog 2 (NW2 and NJ2), and RealFlex Walk 3 (RFW3). All samples that show to be different from the undisturbed soil have an enrichment of this size fraction (Figure 30; Table 9).

The 130-60 micron size fraction was affected by the soil transfer process, but does not appear to be sensitive to any one variable (soil moisture, shoe style, or walking versus jogging). Only two soil samples out of all three transfers match with the undisturbed soil sample: Zignano Jog 1 (ZJ1) and RealFlex Walk 2 (RFW2). All other transferred soil samples show to be different compared to the undisturbed soil, and similar to the >130 micron size fraction, these samples have a higher percentage of this size fraction in comparison to the undisturbed soil (Figure 30; Table 9).

Similar to this size fraction from Rock Creek Park, the 60-41 micron size fraction appears to be the least sensitive to soil moisture, shoe style, and walking versus jogging (Figure 31; Table 8). Of the 18 transfers, only 4 (22%) did not pass the t-test. These include Nike Air Pegasus Walk 1 (NW1), Zignano Jog 1 (ZJ1), Nike Air Pegasus Jog 2 (NJ2), and RealFlex Walk 3 (RFW3). Of the four transferred soil samples that show to be different compared to the undisturbed soil, three are enriched in the size fraction (NW1, NJ2, and RFW3), and one had a lower percentage (ZJ1).

In the <41 micron size fraction, every transferred soil sample from all three transfer sessions shows to be significantly different compared to the undisturbed soil.

(Figure 33; Table 9). These samples all have a lower percentage of this size fraction compared to the undisturbed soil. Although this size fraction is clearly affected by the soil transfer process, at this time, it cannot be inferred that this size fraction is sensitive to any specific variable, including soil moisture, shoe style, or walking versus jogging.

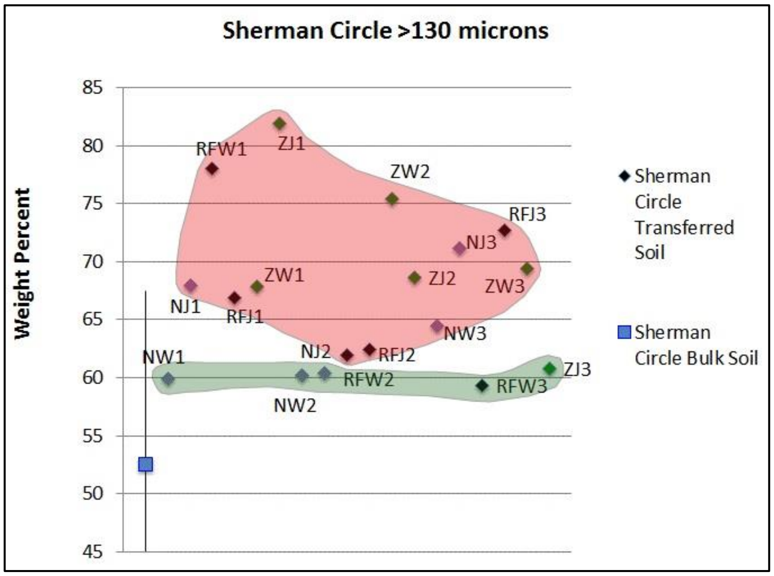


Figure 30 Relative weight percent for the Sherman Circle transferred soil (diamonds) compared to the undisturbed soil (blue square) for the >130 micron size fraction.

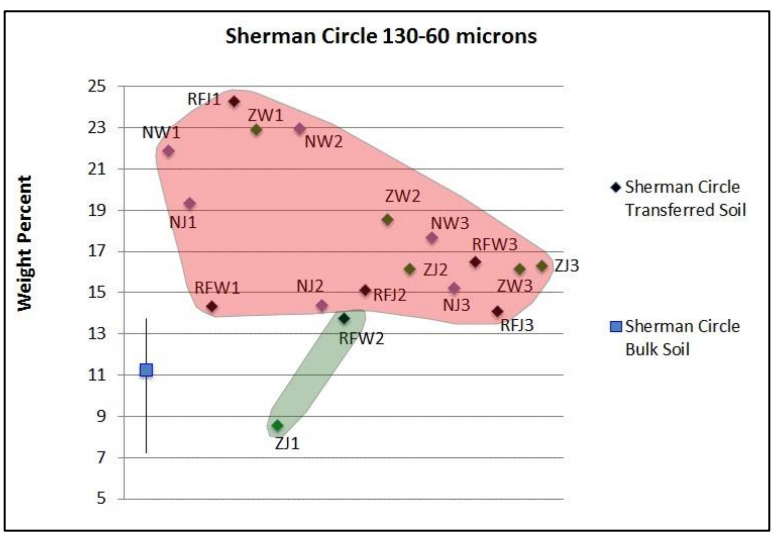


Figure 31 Relative weight percent for the Sherman Circle transferred soil (diamonds) compared to the undisturbed soil (blue square) for the 130-60 micron size fraction.

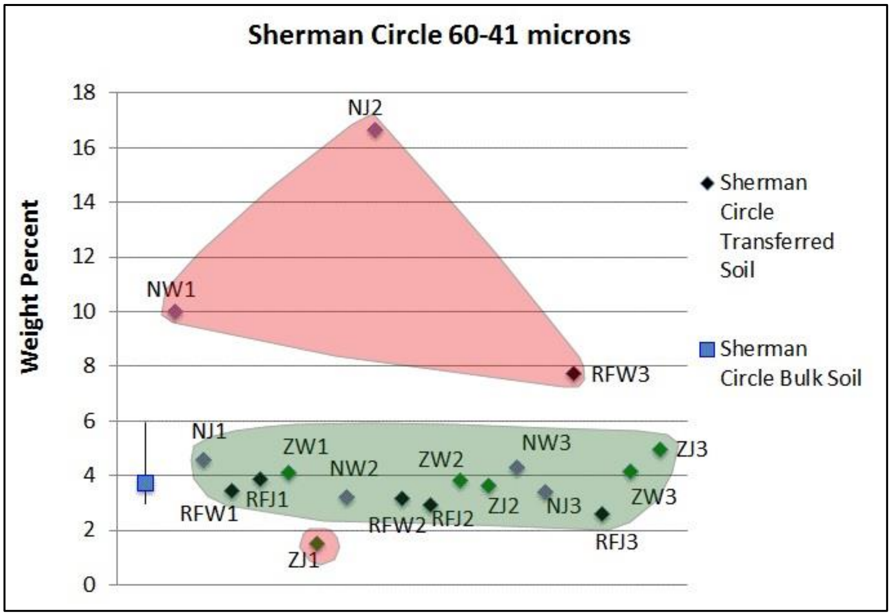


Figure 32 Relative weight percent for the Sherman Circle transferred soil (diamonds) compared to the undisturbed soil (blue square) for the 60-41 micron size fraction.

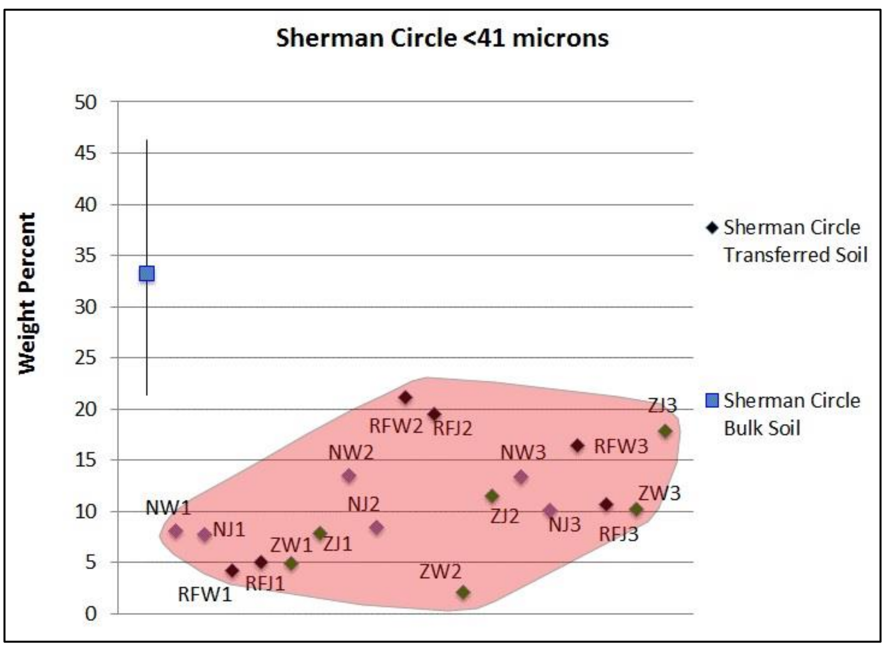


Figure 33 Relative weight percent for the Sherman Circle transferred soil (diamonds) compared to the undisturbed soil (blue square) for the < 41 micron size fraction.

Marvin Gaye Park

The >130 micron size fraction appears to be sensitive to soil moisture, but not shoe style or walking versus jogging during the soil transfer process. The soil moisture content during transfer 1 was the highest of the three transfers, at 5.3%; this transfer had 4 of the 6 samples match the undisturbed soil: Nike Air Pegasus Walk and Jog (NW1 and NJ1), RealFlex Walk (RFW1), and Zignano Walk (ZW1). The two samples that did not pass the t-test had a lower percentage of this size fraction (a depletion of the >130 micron size fraction). Transfer 2, which had a lower measured soil moisture of 3.1%, also had 4 of the 6 samples match the undisturbed soil (Table 10). The two samples that did not pass the t-test (RFW2 and ZJ2) were enriched and depleted in this size fraction, respectively. Transfer 3 had the lowest recorded soil moisture (0.36%), with none of the soil samples matching the undisturbed soil. Most of the samples from transfer 3 have a depletion of this size fraction, with the exception being the RealFlex Walk (RFW3), which is slightly enriched compared to the undisturbed soil (Figure 34).

Similar to Sherman Circle and Rock Creek Park, the 130-60 micron size fraction appears to be sensitive to the soil transfer process, but it is not clear how or if it is affected by soil moisture, shoe style, or walking versus jogging independently. Of the three transfers, only one sample passed the t-test: RealFlex Walk 2 (RFW2). Most of the other samples show a strong enrichment of this size fraction compared to the undisturbed soil, with the exception being RealFlex Walk 3, which has a small depletion of this size fraction (Figure 35).

In the 60-41 micron size fraction, only 3 of the 18 soil samples (17%) from the three transfers match the undisturbed soil (Figure 32; Table 10). These are RealFlex Walk 2 (RFW2), Zignano Walk 2 (ZW2), and RealFlex Walk 3 (RFW3). All other transferred soil is statistically different compared to the undisturbed soil, with all but one sample (NW1) having a higher percentage of this size fraction. There does not appear to be a clear trend in soil transfer behavior according to soil moisture or shoe style, and a weak pattern according to walking versus jogging (all soil samples matching the undisturbed were from walking transfers).

Like Rock Creek Park, the <41 micron size fraction appears to be sensitive to soil moisture, but not shoe style or walking versus jogging, during the soil transfer process. During Transfer 1, with the highest soil moisture (5.3%), all of the transferred soils match the undisturbed soil. Transfer 2, with a lower soil moisture (3.1%) only has 33% of the samples match the undisturbed soil (RFJ2 and ZJ2). The remaining soil samples all have a lower percentage of this size fraction compared to the undisturbed soil. Interestingly, transfer 3, with the lowest soil moisture (0.36%), has 67% of the transferred soil samples match the undisturbed soil. The two different samples, RealFlex Walk (RFW3) and Zignano Walk (ZW3) having a depletion and enrichment compared to the undisturbed soil, respectively (Figure 32).

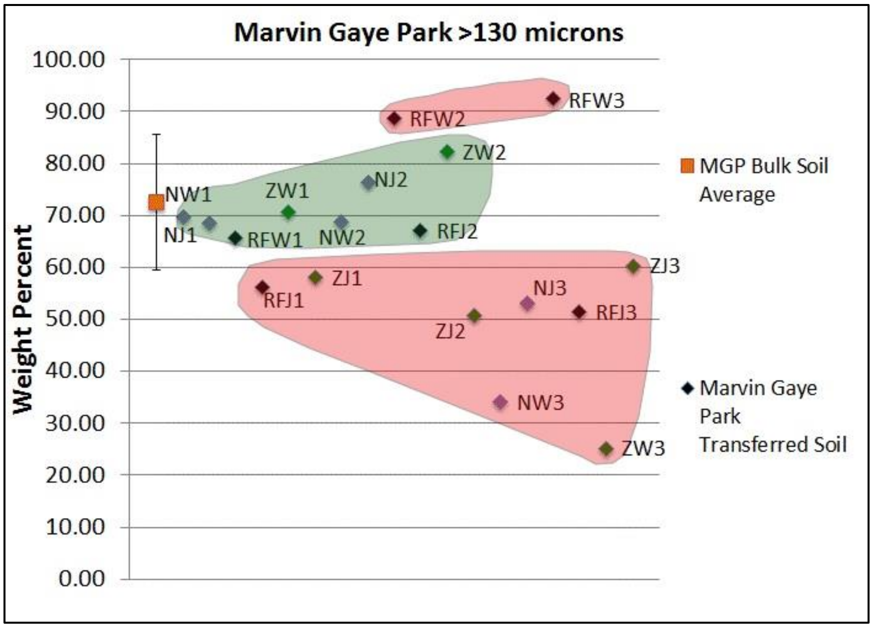


Figure 34 Relative weight percent for the Marvin Gaye Park transferred soil (diamonds) compared to the undisturbed soil (orange square) for the > 130 micron size fraction.

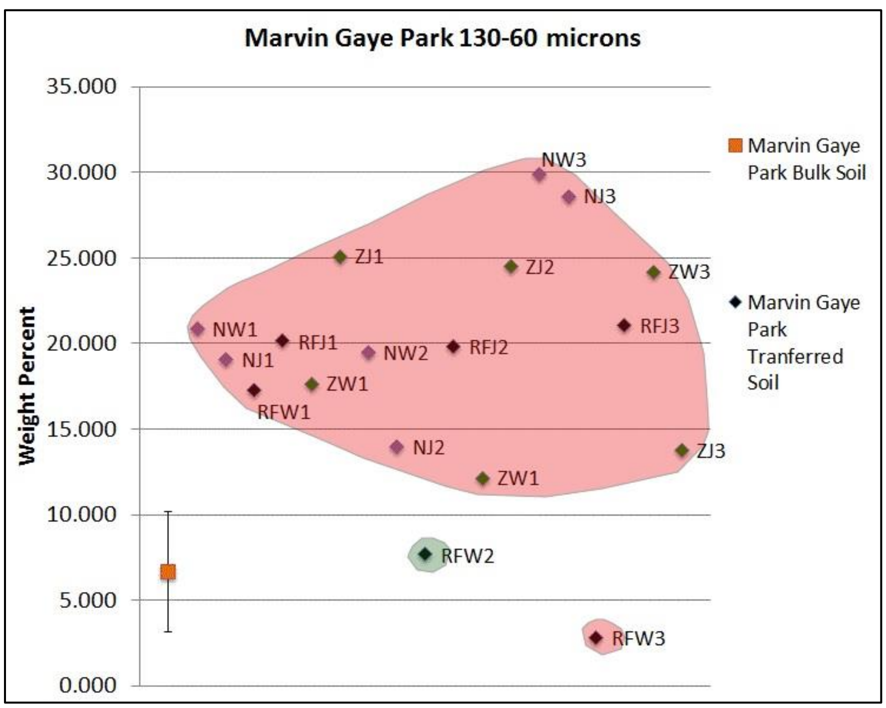


Figure 35 Relative weight percent for the Marvin Gaye Park transferred soil (diamonds) compared to the undisturbed soil (orange square) for the 130-60 size fraction.

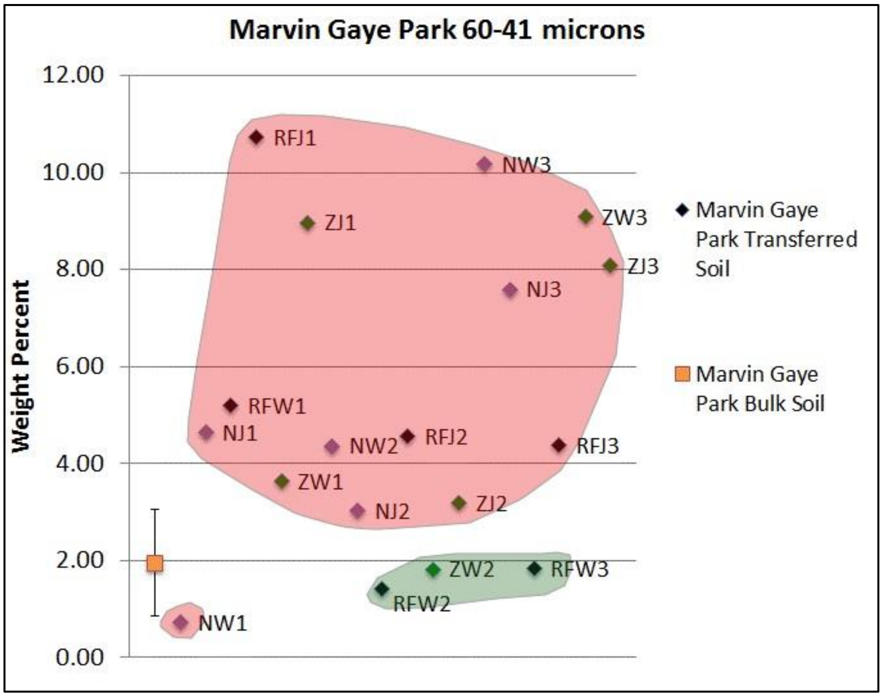


Figure 36 Relative weight percent for the Marvin Gaye Park transferred soil (diamonds) compared to the undisturbed soil (orange square) for the 60-41 micron size fraction.

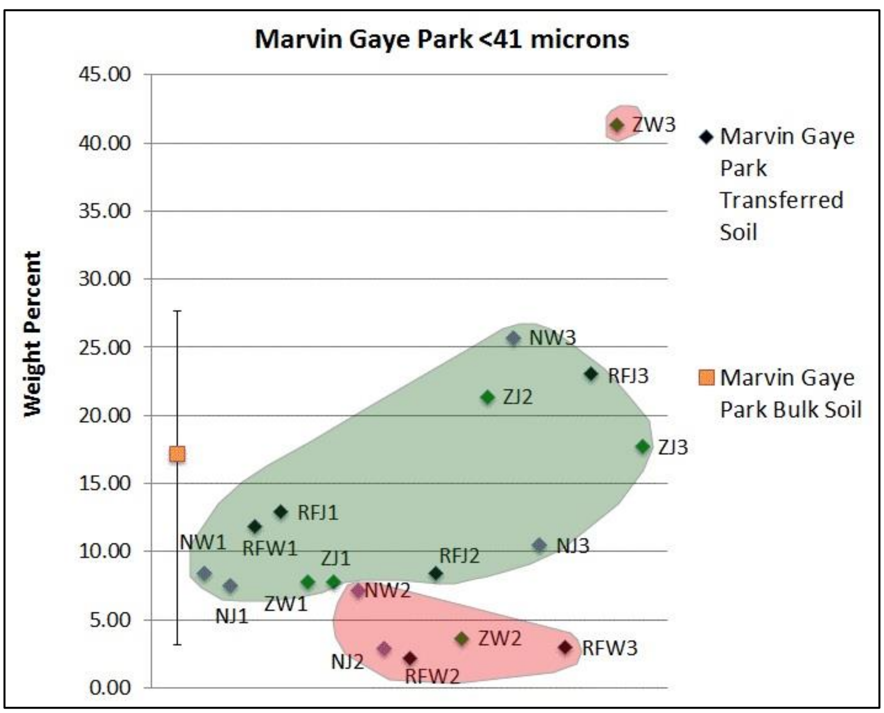


Figure 37 Relative weight percent for the Marvin Gaye Park transferred soil (diamonds) compared to the undisturbed soil (orange square) for the < 41 micron size fraction.

Soil Color Measurements

Soil color measurements were entered in MATLAB using a customized 3-dimensional scatter plot code. The soil color measurements from each sampled location were separated according to individual size fraction and plotted, along with data from the undisturbed sample, for visual comparison (Figures 38-40, below).

An analysis of variance (ANOVA) was performed on this set of data to determine the presence and extent of soil color variation within or between sample locations. In ANOVA, the parameters to be specified are the *experimental treatment, population,* and *factors* (Johnson and Kurby, 2010). Regarding the soil color measurements, a population refers to a sampling location, e.g., Sherman Circle, each measurement of soil color is referred to as a treatment, and the factors are the observations of color – the L, a, and b values.

ANOVA analyses include sum of squares values, mean square values, and a critical value. Total sum of squares (SS) is a measure of total variation in the data and is defined as the sum of all squared deviations around the grand mean. The total sum of squares can be divided into the sum of squares due to error (SS Error)

$$(10)\ \text{SS Error} = \sum (x^2) - \left(\frac{C1^2}{k1} + \frac{C2^2}{k2} + \frac{C3^2}{k3} + \cdots\right)$$

and the sum of squares due to factor (SS Factor).

$$(11)\ \text{SS Factor} = \left(\frac{C1^2}{k1} + \frac{C2^2}{k2} + \frac{C3^2}{k3} + \cdots\right) - \left(\frac{(\sum x)^2}{n}\right)$$

The sum of squares is a quantitative assessment of the total variation within a sample population or between populations, taking into account a measurement's deviation from the sample mean.

Mean square error (MS Error) and mean square factors (MS Factor) are calculated by dividing the corresponding sum of squares by the number of degrees of freedom. Although the sum of squares values are additive, that is, it value becomes larger with increasing sample size, mean square values are scaled according to sample size (dividing by degrees of freedom, vide infra), and the value is no longer additive. Comparing the mean square values within and between samples will ultimately determine statistical significance.

$$(12)\ \text{MS Error} = \frac{SS\ Error}{DF\ Error}$$

$$(13)\ \text{MS Factor} = \frac{SS\ Factor}{DF\ Factor}$$

In the equations above, x is the value of an individual measurement, c is the sum of measurements of a sample variable (e.g. the sum of all "L" values for sample RC 1 >130 µm fraction), k is the number of replicates taken for a sample, n is the total number of measurements taken for that set of data ($\sum k_i$), and DF is the corresponding degrees of freedom.

Each sample has 3 types of degrees of freedom associated with it. These are (1) total degrees of freedom (DF Total), (2) degrees of freedom associated with error (DF Error) and degrees of freedom associated with factor (DF Factor). Total DF is defined as n-1, where n is the number of replicates taken (e.g. $\sum$ k). Alternatively, n can be defined as the product of c•k. DF error is defined as n-c, where c is the number of treatments (e.g. for intra-site variability, c is 6 for the six sub samples), and DF factor is defined as c-1.

The calculations defined in equation set 3 above are used in the F distribution, which is used to make interpretations about the ratio of two independent populations. The F distribution is used when it is known or assumed that the populations are normally distributed. The F test compares two or more populations' variances, and is the basis of ANOVA. In this study, an F distribution with an α-value of 0.05 is being used, which means that 5% of the area under the F distribution curve lies in the critical region (statistically significant). Values that are higher than the critical value are statistically significant because values larger than the F Critical value indicate that the samples are not equal, and are therefore significantly different.

The F statistic for any given set of measurements is calculated as:

$$(14)\ \text{F Statistic} = \frac{MS\ Factor}{MS\ Error}$$

Variation of soil color for a given site is significantly different if the F statistic value for a given parameter is greater than the corresponding F critical value (standard values relating to the number of degrees of freedom for the samples).

In this study, if a calculated F statistic is less than the F critical value, we can infer that the soil samples are similar. This concept can be visualized in the soil color plots: a tighter cluster of points indicates a smaller amount of variability. The results of the ANOVA calculations are presented in Table 11, and an example set of ANOVA calculations used in this study is given in Appendix 5.

The minimum necessary sample mass suitable for digital color measurements is ~0.5 grams. This is important considering the low amount of sample material recovered (0.1 grams or less in this study) from the shoes. Samples highlighted in Table 3 reflect those that did not yield enough soil material to take soil color measurements. During the process of obtaining soil color, the soil samples experienced a reduction in mass that was observed to be $\leq$ 0.1 gram. This is due to some of the soil adhering to the colorimeter surface, which was not recovered. To account for this loss of material, particle size percentages were calculated based on the sum of the weights of the individual size fractions, and not according to the initial reference weight of the bulk soil sample.

Applying ANOVA to the color measurements for the unsieved, undisturbed soil, both the Rock Creek Park and Marvin Gaye Park samples exhibit significant intra-site variation in soil color, whereas Sherman Circle samples do not. This is summarized in the first three elements of the top row for Table 11. These relationships can be seen qualitatively from the dispersion of individual unsieved color measurements for each locality shown in Figure 38. There is no significant difference in soil color for the individual size fractions from Rock Creek Park. In contrast, the Marvin Gaye Park individual size fractions exhibit a significant difference in soil color, as do two of the Sherman Circle individual size fractions: the coarsest (>130 μm) and finest (< 41 μm) size fractions (Table 11).

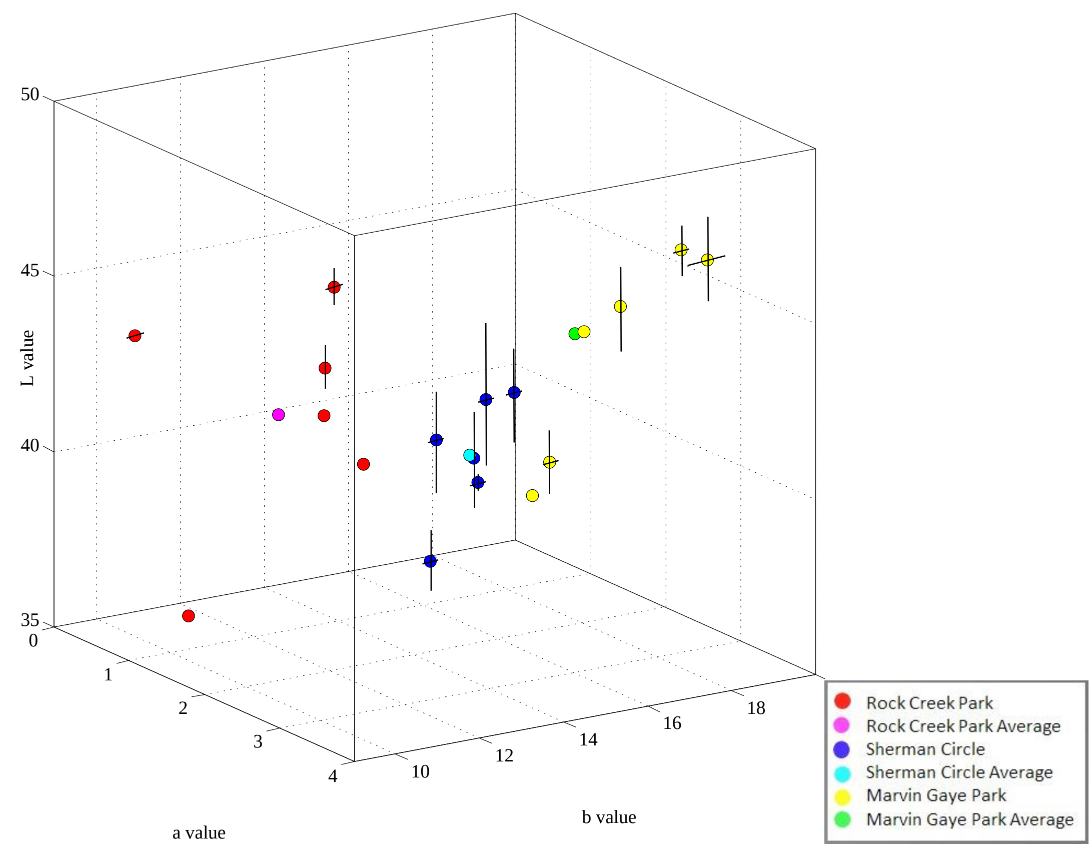


Figure 38 3-d plot of undisturbed soil color from the three sample locations: Rock Creek Park (red), Sherman Circle (blue) and Marvin Gaye Park (yellow). Average values for each set of soil color data are also plotted in magenta (Rock Creek Park), cyan (Sherman Circle), and green (Marvin Gaye Park). Bars extending from data points represent variability in soil color values. Where bars are not shown, variability was smaller than a bar could represent.

When comparing color for both sieved and unsieved soil samples, between any two sites or among all three, the only pairing that did not show a significant difference in color was the Rock Creek Park-Marvin Gaye Park (RCP-MGP) unsieved soil comparison. All of the color measurements for the sieved soil samples in the inter-site soil color comparison analysis showed a significant difference (last four columns of Table 11, for the sieved samples). I suggest that, for future forensic studies, color comparisons between any two given undisturbed soil samples should employ the 130-60 micron and 60-41 micron size fractions.

	Intra-site Variation			Inter-site Variation			
	RCP	SHC	MGP	RCP-SHC	RCP-MGP	SHC-MGP	RCP-MGP - SHC
Unsieved Soil Sample	X(L,a,b)	-	X(L,a,b)	X (L,a,b)	-	X(L,a,b)	X(L,a,b)
> 130 µm	-	X(L,a,b)	X(L,a,b)	X (L,a,b)	X (a,b)	X (L,a,b)	X (L,a,b)
130 – 60 µm	-	-	X(L,a,b)	X (L,a,b)	X (a,b)	X (L,a,b)	X (L,a,b)
60 – 41 µm	-	-	X(L,a,b)	X (L,a,b)	X (a,b)	X (L,a,b)	X (L,a,b)
< 41 µm	-	X(L,a,b)	X(L,a,b)	X (L,a,b)	X (a,b)	X (L,a,b)	X (L,a,b)

Table 11 Results of ANOVA calculations for quantitative analysis of color for undisturbed soils of this study. Abbreviations are as follows: RCP: Rock Creek Park, SHC: Sherman Circle, MGP: Marvin Gaye Park. X = Significantly different; a dash in the box signifies no significant difference.

Soil color measurements on the individual size fractions are related in a complex manner to the color of the undisturbed soil (Figure 38). Soil color changes upon sieving, and it is important to understand this phenomenon in order to determine which size fractions(s) are the best match to soil material collected from shoes. Note from Figure 14 that the undisturbed soil is darker in color (i.e. has a lower L* value than any of the constituent size fractions). This effect is most likely due to the loss of the organic fraction upon wet sieving. The 60-41 micron fraction in many of the soils is the darkest sieved fraction, most likely due to the presence of ferromagnesian minerals. Quartz and feldspar characterize the >130 micron fraction, yielding a relatively high L* value.

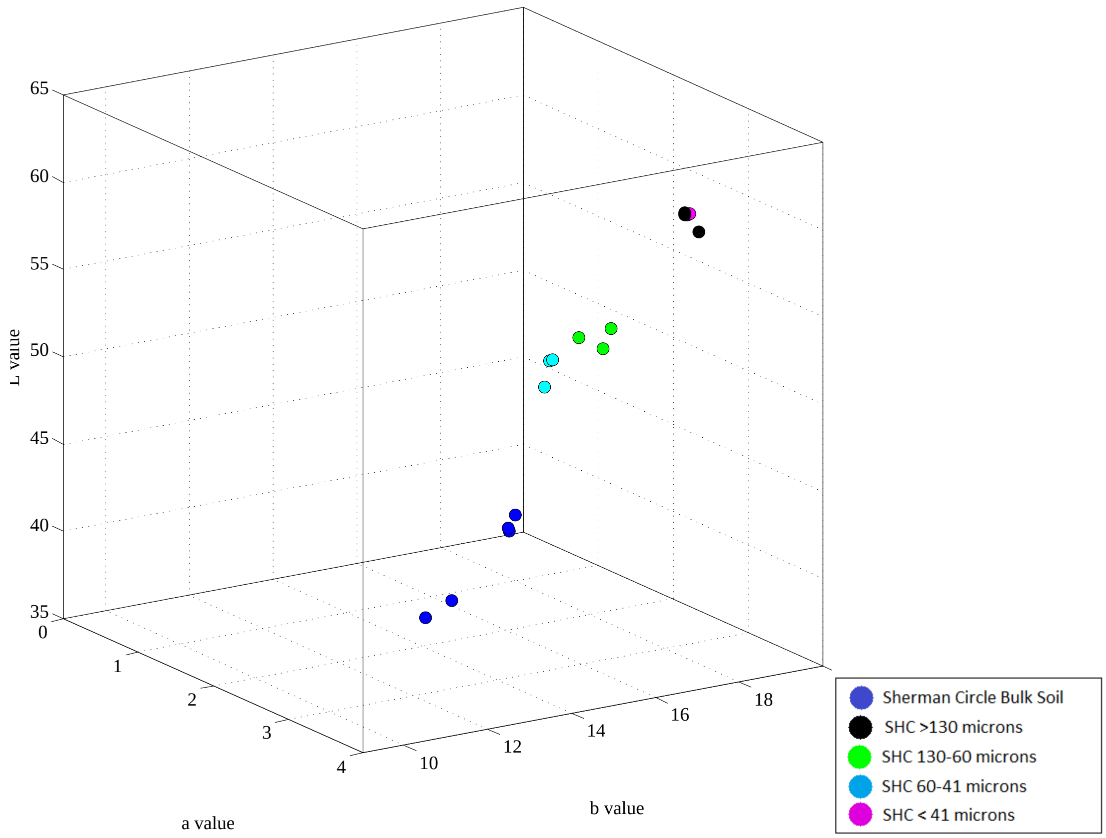


Figure 39 3-d plot of undisturbed soil sample color measurements from Sherman Circle sample 1. This plot shows how the undisturbed soil sample color (plotted in dark blue) can differ from the individual size fractions. Although the a* and b* values are minimally shifted, there is a noticeable increase in the L* values.

The transferred soil material (Figures 40) generally plotted within a trend of the respective location, with slightly higher L and b values. None of the Marvin Gaye Park transferred soil samples yielded enough material to obtain soil color measurements. Soil color plots comparing the transferred soil with the different size fractions of the undisturbed soil are given in Appendix 10.

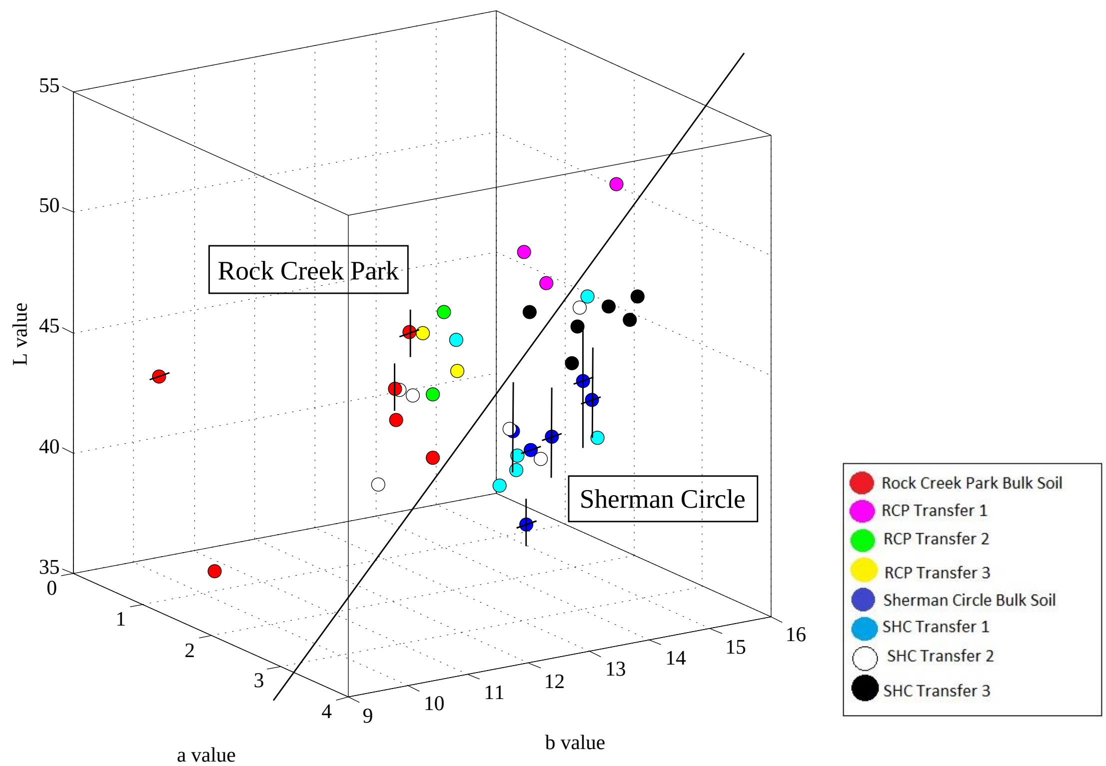


Figure 40 3-d plot of undisturbed and transferred soil average sample color measurements from Sherman Circle and Rock Creek Park. Bars extending from data points represent variability in soil color values. Where bars are not shown, variability was smaller than a bar could represent.

The statistical analyses of the color data for comparisons between undisturbed and transferred soil are given in Tables 12 and 13. Two types of tests were used in these comparisons: an analysis of variance (ANOVA) and a t-test. Both of these statistical analyses have been used in previous forensic studies (Croft and Pye, 2004a; 2004b, Guedes et al., 2009). The goals of this study are to understand the soil transfer process while also capturing the maximum soil variability at a location; this undoubtedly affects the outcome of the statistical analyses in that this variability will be more pronounced in the ANOVA statistical analyses. For this reason, it is important to show the results of both the ANOVA and t-test, and see how the compare.

	RCP Transfer1	RCP Transfer2	RCP Transfer3	SHC Transfer1	SHC Transfer2	SHC Transfer3
Whole Soil	X	X	X	-	-	X
>130 µm	X	X	X	X	X	X
130-60 µm	X	X	X	X	X	X
60-41 µm	X	X	X	X	X	X
< 41 µm	X	X	X	X	X	X

Table 12 ANOVA calculations for soil color comparisons between Rock Creek Park (RCP) and Sherman Circle (SHC) undisturbed and transferred samples. Significantly different for every shoe during that transfer (X); no significant difference in at least one of the shoes during that transfer (-).

	RCP Transfer1	RCP Transfer2	RCP Transfer3	SHC Transfer1	SHC Transfer2	SHC Transfer3
Whole Soil	X	X	X	-	-	X
>130 µm	X	X	X	X	X	X
130-60 µm	X	X	X	X	X	X
60-41 µm	X	X	X	X	X	X
< 41 µm	X	X	X	X	X	X

Table 13 t-test calculations for soil color comparisons between Rock Creek Park (RCP) and Sherman Circle (SHC) undisturbed and transferred samples. Significantly different for every shoe during that transfer (X); no significant difference in at least one of the shoes during that transfer (-).

Based on the ANOVA, only two of the 30 samples of transferred soil were shown to be derived from the same population as the undisturbed soil. Sherman Circle Transfer 1 and Sherman Circle Transfer 2 each had at least one shoe sample match the whole, unsieved undisturbed soil sample. The rest of the transferred samples fail compared to the undisturbed soil in every size fraction for every transfer.

The number of matches increases to 11 out of 30 in the t-test results (which includes the same 2 matches from the ANOVA analyses). Out of all three transfers, Rock Creek Park had a total of 3 matches, one in each of the 130-60 micron, 60-41 micron, and < 41 micron size fractions (Table 13). More than half (8 of the 15) of the transferred samples from Sherman Circle match the undisturbed soil based on the t-test. These matches come from the 130-60 micron and 60-41 micron size fractions, where all of the transfers had at least one shoe match, as well as the whole, unsieved undisturbed soil, where 2 of the transfers had at least one shoe match.

There is no obvious relationship between shoe of transfer (walking versus jogging) style and the corresponding size fraction of the undisturbed soil. Further, all of the samples with a match only passed with the L* component of soil in both the ANOVA and t-test analyses; the a* and b* components all failed to match the undisturbed soil samples even when the L* value for that same sample matched. More reliable soil color results have been published by Croft and Pye (2004a), comparing the transferred soil (ground to a < 10 micron powder) with undisturbed soil that has been sieved to the < 150 micron fraction and then ground to a < 10 micron powder.

Heavy Mineral Analysis

The heavy mineral analysis was performed on the 130-60 μm size fraction from all sample sites. The heavy mineral component of all control samples was analyzed optically using a binocular microscope, and visually and chemically using standard backscattered electron and energy dispersive spectroscopy techniques.

The mineralogy for each location was determined by combining the elemental composition, morphology, and texture of the particles. Particles were analyzed in a grid pattern, and relative abundances of each mineral were noted. A comparison of mineralogy is given in Table 14.

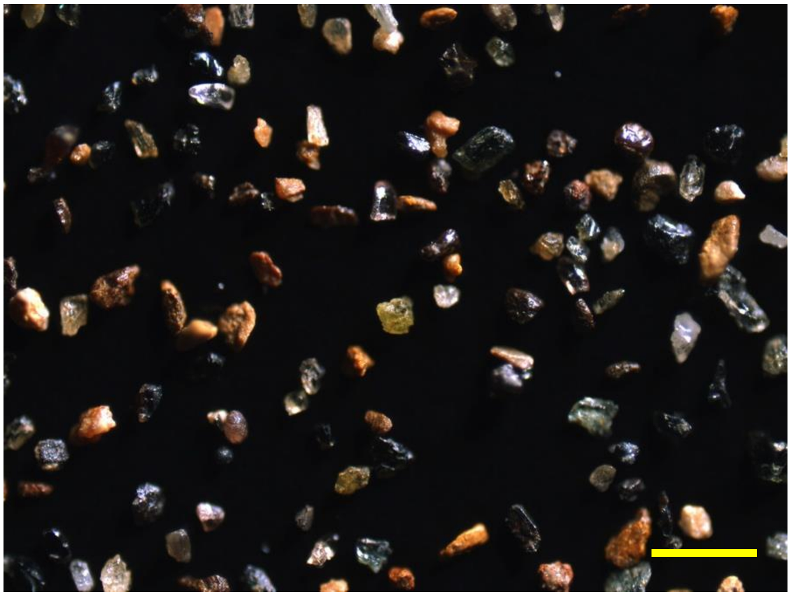


Figure 41 Field of view showing the heavy mineral fraction from sample SHC 1. Scale bar is 0.5 mm.

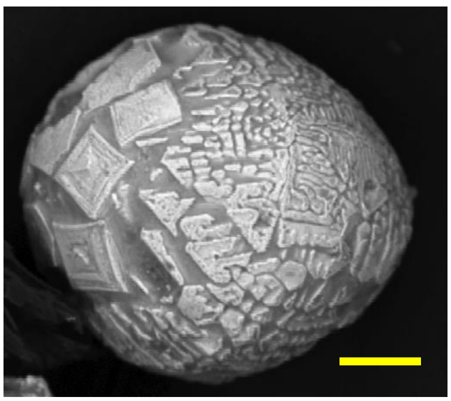
The Rock Creek Park heavy mineral suite included an abundance of euhedral magnetite (Figure 44), ilmenite, rutile, euhedral and subhedral zircons, garnets, epidote, apatite, anhedral monazite, and iron oxide spheres (Figure 45). These iron oxide spheres were not unique to Rock Creek Park; however, the abundance of and textures of the spheres could be useful in forensic analyses. Even though tourmaline has been reported in the heavy mineral fractions of samples sourced from the Piedmont Province (Groot and Glass, 1960), none were observed in the soil samples from Rock Creek Park, which is in this Province.

At Sherman Circle, identified minerals include garnet, epidote, hematite, tourmaline, diopside, monazite, and zircon (Table 14). Backscatter electron images of grains from the Sherman Circle location (Figures 42 and 43) show interesting textures in some iron oxide spheres, including dendritic and micrographic texture. The only mineral not identified in this sample compared to Rock Creek Park is apatite. A large portion of the other minerals were noticeably more rounded and fractured compared to the minerals at Rock Creek Park. The likely cause of this rounding and fracturing is due to transportation of these minerals downstream from the Piedmont. The fact that apatite was not seen in the Sherman Circle samples could be due to this mineral becoming reduced in concentration as mineral transportation occurred.

In the heavy mineral fraction from Marvin Gaye Park, there were euhedral-to-subhedral magnetite grains, anhedral hematite and ilmenite grains, an abundance of subhedral and hemispherical zircons (Figure 46), tourmaline (Figure 47), apatite, as well as iron oxide spheres identified, though these were seen in much lower abundances compared with the other two locations. Compared to Rock Creek Park and Sherman Circle, there was less garnet and epidote in these samples, possibly due to the increased distance from the sediment source material. These observations match with those of Groot and Glass (1960). There was a titanium dioxide sphere in the Marvin Gaye Park sample, which was not observed in the other two; further study is needed to indicate whether these grains are unique to the location. Iron oxides, titanium dioxides, and some silicate minerals were identified based on chemistry from EDS (utilizing ratios of peak heights in discriminating between minerals with similar chemical compositions) in conjunction with grain morphology. Additionally, even though zircon was identified at all three locations, the morphology and surface texture of the zircons were all distinct. Phase and morphology comparisons could be used in forensic soil comparisons as supporting evidence in determining how likely it is that two samples are from the same location. Abundances are meant to be qualitative only. Additional images of the minerals from these locations are in Appendix 8.

Mineral | Location	Rock Creek Park	Sherman Circle	Marvin Gaye Park
Magnetite*	Abundant anhedral to euhedral	Mostly anhedral	Anhedral
Hematite	X	Blocky, scratched surfaces	Anhedral
Ilmenite	Subhedral-anhedral	Subhedral-anhedral	Abundant Rounded, elongate, pitted surface
Rutile	Subhedral	Abundant as coatings on other minerals	Abundant euhedral and anhedral
Zircon	Abundant euhedral-anhedral	Subhedral-anhedral	Abundant hemispheres and subhedral
Garnet	Euhedral-subhedral-anhedral	Subhedral-anhedral; iron-stained	X
Monazite	Anhedral	Anhedral	X
Tourmaline	X	Euhedral-subhedral	Subhedral
Apatite	Euhedral-subhedral	X	Anhedral, pitted surface
Epidote	Subhedral, pitted	Subhedral	X
Diopside	X	Subhedral	X
Iron Oxide Spheres*	Smooth, dendritic, myrmekitic textures	Granophyre/dendritic textures	Dendritic, cracked, blocky textures
Titanium Dioxide Spheres*	X	X	Dendritic texture
* = from magnetic fraction			
X= not found			

Table 14 Heavy mineral assemblages of the 130-60 µm size fractions from the three sample locations. X= mineral was not found at that location; * = analyzed from the magnetic mineral fraction.



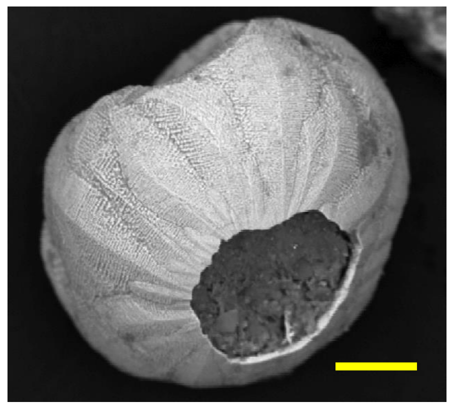
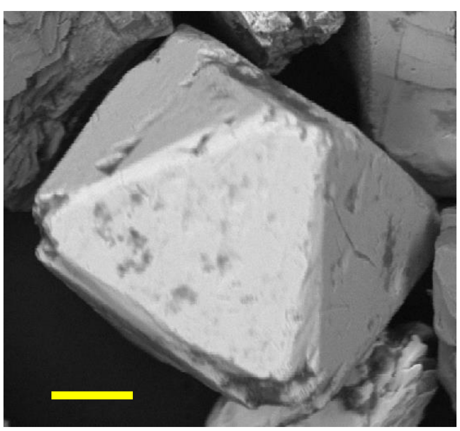


Figure 42 (left) and 43 (right) Iron oxide spheres with micrographic (left) and dendritic (right) textures in the heavy mineral fraction of Sherman Circle. Scale bar 20 microns.



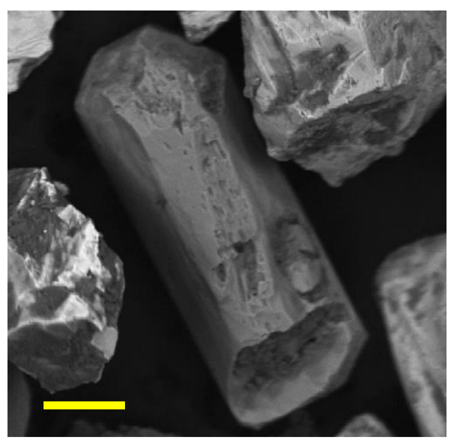
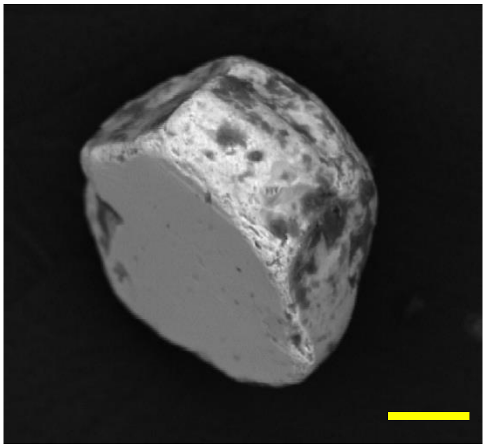
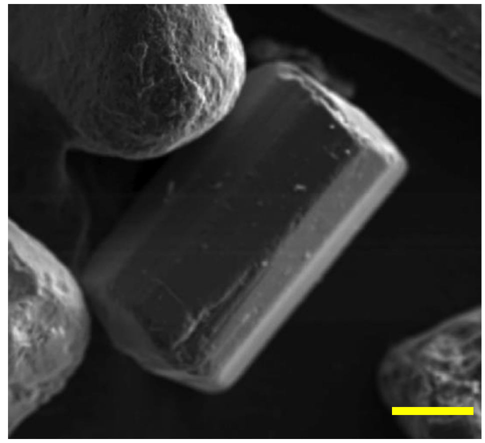


Figure 44 (left) and 45 (right) Euhedral magnetite (left) and subhedral apatite (right) in the heavy mineral fraction of Rock Creek Park. Scale bar 20 microns.

Figures 46 (left) and 47 (right) Hemispherical zircon and subhedral tourmaline in the heavy mineral fraction of Marvin Gaye Park. Scale bar 20 microns.

XRD Data

X-ray diffraction (XRD) data were collected at the University of Maryland's X-ray Crystallographic Center with a Bruker C2 Discover diffractometer. This machine employs a Cu-Kα sealed x-ray tube with Göbbel mirror. The samples submitted for comparative analysis were the undisturbed soil samples for all three locations, as well as the individual size fractions for Rock Creek Park. Ideally, 0.5-1.0 grams of soil are necessary for XRD analysis, with a recommendation of at least 0.2 grams (Dr. P. Zavalij, University of Maryland X-ray Crystallographic Center, Personal Communication). Below this, the quality of the analysis decreases. From this experiment, 37% of the transferred soil samples do not meet the ideal mass requirement for analysis, and 20% of the transferred soil samples would not meet the recommended minimum amount (Table 3). Most of the samples obtained from the transfer experiments that would not qualify for XRD analysis come from the Reebok Zignano, but also from the Nike Air Pegasus and the Reebok RealFlex, and especially from the Marvin Gaye Park location.

X-ray diffraction data for the three sample locations (Figures 47 and 48) show similarities and differences in the mineral phases. Overall, the main peaks in all three spectra are similar, suggestive of a similar major-mineral assemblage among the samples. However, minor peaks tell a different story. For example, the spectra from the Rock Creek Park sample, contains major serpentine peaks (identified as var. lizardite), and chlorite, whereas these are present in lower concentrations at Sherman Circle, and absent from Marvin Gaye Park. The reduction or absence of chlorite and serpentine at Sherman Circle and Marvin Gaye Park, which are both composed of Cretaceous nonmarine sediments, are in agreement with the findings of Groot and Glass (1960).

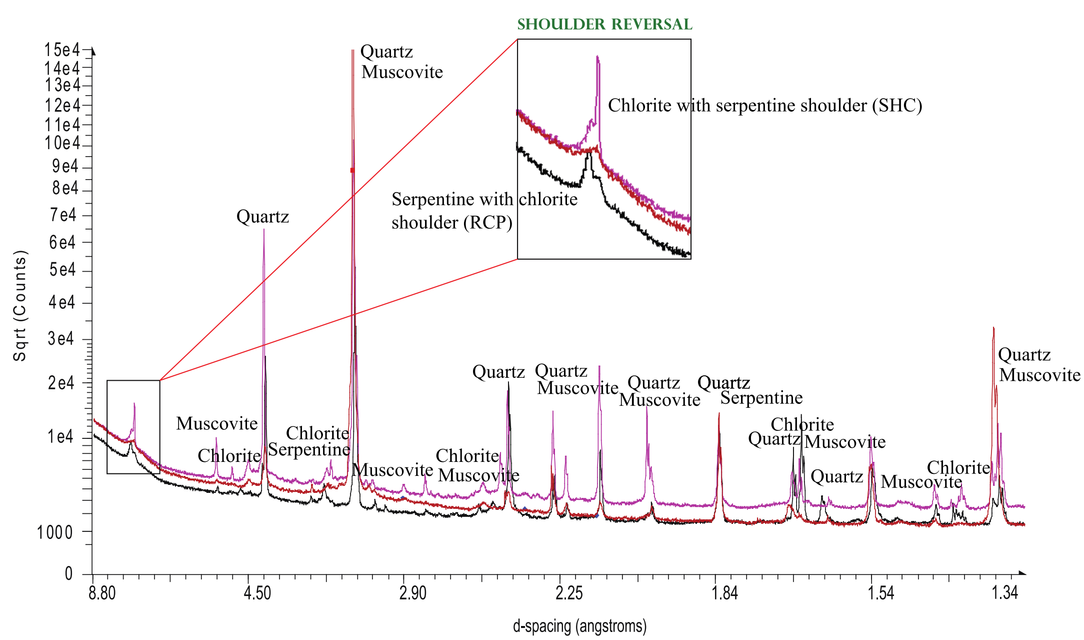


Figure 48 XRD patterns for bulk soil samples of the three locations. Rock Creek Park (black), Sherman Circle (magenta), and Marvin Gaye Park (red).

The bulk soil mineralogy was also compared with individual size fractions for the Rock Creek Park sample (Figure 48). The only noticeable differences in mineralogy were in the <41 μm fraction, which yielded more clay mineral peaks (d spacings < 20 Å).

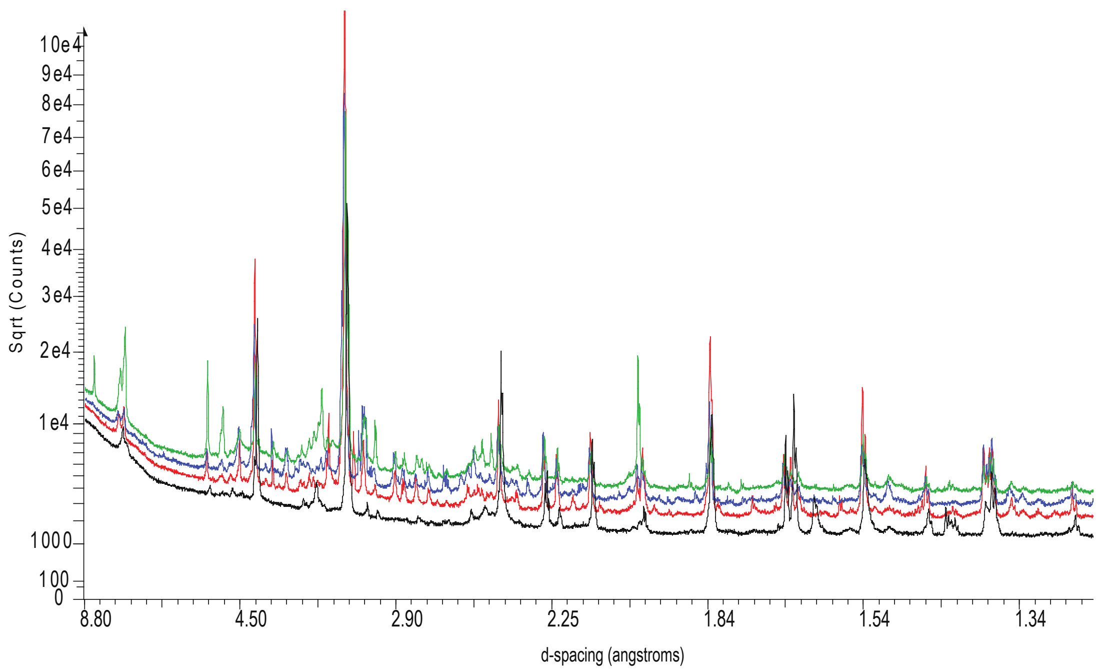


Figure 49 XRD patterns for the bulk and individual size fractions of Rock Creek Park. Bulk soil (black), 130-60 μm (red), 60-41 μm (blue) and <41 μm (green).

Mineral | Location	**Rock Creek Park**	**Sherman Circle**	**Marvin Gaye Park**
Quartz	X	X	X
Serpentine	X	X	
Chlorite	X	X	
Muscovite		X	X
X= present			

Table 15 XRD mineralogy comparison of the undisturbed, bulk soil material for the three sample locations. X= present.

Major minerals identified in the bulk soil from Rock Creek Park include quartz, serpentine, and chlorite. All of these minerals were present in Sherman Circle, with the addition of muscovite. However, serpentine was only identifiable as minor peaks in the Sherman Circle sample, which is consistent with the likely reduction of this mineral as distance from the source material increases. The only identifiable phases in the Marvin Gaye Park XRD pattern are quartz and muscovite, indicating a loss of these minerals, again, possibly as a result of the increased distance from the source material.

Chapter 7: Interpretation and Discussion

Particle size distribution

The differences in particle size distribution at each sample collection site could be due to several factors beyond those tested here as a part of this work. These include sample distance to the sidewalk or street curb or distance from trees. These factors may influence how much rain is received, whether any street or other urban debris (e.g. litter, building materials) is present, and the amount of foot traffic upon the surface. Undisturbed soil samples at Sherman Circle and Marvin Gaye Park were collected with the intent to capture the maximum variability in soil properties as observed visually in the field, so as to obtain an estimate of the range of soil properties within a location. Any or all of these factors may affect the particle size population of a given sample, resulting in the anomalous relative enrichment or depletion of particles that populate given size fractions, in comparison to the other samples.

Comparing the particle size distributions of the transferred soil with the soils from other locations yielded some interesting results. For Rock Creek Park, 15 of the 18 transferred soil samples from that location matched the control soil in the 60-41 micron size fraction. The number of samples matching the undisturbed soil reduced to 4 of 18 samples when comparing the transferred soil from Marvin Gaye Park to Rock Creek Park and to only 1 of 18 when comparing the transferred soil from Sherman Circle to Rock Creek Park (Appendix 9). A similar pattern follows for the other size fractions. In the >130 micron fraction, 4 of 18 transferred samples from Rock Creek Park match the corresponding undisturbed soil, which is reduced to 3 of 18 and 1 of

18 matches for transferred soil from Marvin Gaye Park and Sherman Circle, respectively. In the 130-60 micron fraction, 4 of 18 transferred samples from Rock Creek Park match the whole soil, which is reduced to 1 match for both the Marvin Gaye Park and Sherman Circle transferred samples. The <41 micron fraction has 6 of the 18 transferred samples from Rock Creek Park matching the undisturbed soil, with 6 of 18 transferred samples from Sherman Circle also matching the Rock Creek Park undisturbed soil, and 5 samples from Marvin Gaye Park matching Rock Creek Park. The 6 matching samples from Sherman Circle are all from Transfer 1, suggesting that this is due to the higher soil moisture content at the time of transfer (11%).

For Sherman Circle, 14 of the 18 transferred soil samples matched the control soil in the 60-41 micron size fraction. The number of matches in this size fraction was reduced to 7 of 18 when comparing transferred samples from Marvin Gaye Park and to only 1 when comparing transferred samples from Rock Creek Park to the undisturbed Sherman Circle soil. In the >130 micron fraction, 5 of the 18 transferred soil samples from Sherman Circle matched the respective undisturbed soil. When comparing the undisturbed Sherman Circle soil to the transferred samples from Rock Creek Park, the number of matches was reduced to zero in this size fraction; however, when comparing to Marvin Gaye Park, the number of matches increased to 6 of the 18 transferred soil samples. The six samples were spread out throughout all three Transfers and all three shoe types, but were all for “jogging” transfers. In the 130-60 micron fraction, the number of transferred soil matching the control soil was 2 of 18, which was the same number when comparing to the other two locations. None of the transferred soil samples matched the <41micron fraction for Sherman Circle. The number of matches in this fraction was also zero when comparing to Rock Creek Park, but was 2 when comparing the undisturbed soil to the transferred soil from Marvin Gaye Park. The data suggest that for Sherman Circle and Rock Creek Park, the 60-41 micron size fraction is still the best for use in forensic soil comparison.

For Marvin Gaye Park, 12 of the 18 transferred soil samples matched the control soil in the <41micron size fraction, suggesting that this fraction is the one to use in forensic analyses for soils of this type. The number of matches reduced to zero when comparing transferred samples from Rock Creek Park to the Marvin Gaye Park control soil, but actually increased to 14 of the 18 transfers matching when comparing to Sherman Circle. In the >130 micron fraction, 8 of the transferred soil samples matched the control soil. When comparing to the transferred samples from Rock Creek Park, the number of matches stayed at 8 of 18, and when comparing to Sherman Circle, the number of matches again increased to 11 of 18. In the 130-60 micron fraction, only 1 of the 18 transferred soil samples from Marvin Gaye Park matched the control soil. The number of matches stayed the same when comparing to Sherman Circle, and increased to 3 of 18 when comparing to transferred samples from Rock Creek Park. In the 60-41 micron fraction, 3 of the 18 transferred samples matched the undisturbed soil. The number of matches reduced to 2 of 18 when comparing to Sherman Circle transferred samples, and increased to 9 of 18 when comparing this size fraction to the Rock Creek Park transferred samples.

The observed differences in particle size distribution between the undisturbed and transferred soil did not follow any clear pattern according to shoe style, walking versus jogging, or soil moisture content at time of transfer. The results from Rock

Creek Park and Sherman Circle indicate that the 60-41 μm may be the appropriate size fraction for use in comparing particle size population fractions because the undisturbed and transferred soil fractions were not statistically significantly different between the two. However, the results from Marvin Gaye Park contradict these findings. These results indicate that there is an inconsistent (does not follow a pattern according to shoe type, transfer style, or soil moisture content), but statistically significant, bias in particle size distribution between undisturbed soil samples and transferred soil material. None of the transferred soil samples from Marvin Gaye Park yielded enough material to obtain color measurements (Table 3). This low amount of accumulated soil during the transfer process may contribute to a skewed particle size distribution; otherwise, the results suggest that the 60-41 micron size fraction is best for soil sample comparison in forensic analyses. Upon evaluation of the Marvin Gaye Park data as a whole, the finest fraction (< 41 microns) may be a better comparison for samples with low yields. The suggested size fractions are based on the aforementioned results, and may not be the most appropriate for every type of soil. Further study focusing on the effect of soil transfer on the resultant particle size distribution is required to make more definitive conclusions.

Interpretations comparing two urban soils, such as the case of Sherman Circle and Marvin Gaye Park, must be supported with other forms of evidence because there were more matches to this soil using samples from an incorrect location (Sherman Circle) than there were to the appropriate one in the size fraction originally chosen as the best for comparison (< 41 microns). Given the intent of capturing the maximum soil variability during the collection of undisturbed soil at the Sherman Circle and

Marvin Gaye Park locations, the sampling pattern was not randomized. Random sampling increases the likelihood of a population having a normal distribution; because of the sampling pattern used in this study, some of the sample sets may be characterized by non-normal distributions. The assumption that a population has a normal distribution is not always required for the application of a t-test; the t-statistic has yielded useful results even when the sample population is not normally distributed (Sawilosky and Blair, 1992), as long as skewness is not excessive.

Two sets of single sample t-tests were also performed: one set on the raw data (Tables 8-10), and one set on the log-transformed data (Appendix 9). Due to the intent of capturing the maximum soil variability at the urban soil locations Marvin Gaye Park and Sherman Circle, a t-test, which assumes a normal distribution of the population, would not be appropriate for statistically analyzing the particle size distributions from the raw data. However, a t-test was performed on particle size distributions from the raw data of these locations (Tables 9, 10), but because of the non-normalized sample population, the results should be interpreted with caution. At Rock Creek Park, it can be assumed that the soil samples have a normal distribution and therefore a t-test is appropriate in the comparison of soil material from this location.

A log transformation of the data can sometimes produce a distribution that is near-normal. However, the application of the t-test to the log-transformed data did not significantly change the results. In the Rock Creek Park dataset, 5 of the 72 soil samples (7%) changed from being "significantly different" to "not significantly different" or vice versa, with these 5 occurrences in the 60-41 micron and < 41 micron size fractions. In the Sherman Circle dataset, 4 of the 72 soil samples (5.5%) changed after the log transformation. The results of the log transformation were even less noticeable in the Marvin Gaye Park dataset, with only 1 of the 72 samples (about 1.5%) changing. "Normalizing" the raw data did not make a large impact on the interpretation of the data, and therefore does not appear to be a necessity for this statistical analysis, based on the limited sample set collected as part of this study.

Further study is needed to more closely evaluate the effects of soil moisture, seasonal variation, and shoe style on soil transfer to shoes. There are seasonal effects; for example, Rock Creek Park transfer 1 was collected in September and shows an overall coarsening of the sample, whereas Rock Creek Park transfers 2 and 3 were collected in December, and exhibit a decrease in the percentage of the coarse (>130 μm) particle size fraction. At this time, however, these seasonal effects cannot be fit to a generalized trend.

Sugita and Marumo (2001) suggest that reducing the number of particle size fractions used in sieving three (<50 μm, 50-200 μm, and 200-2,000 μm) minimizes the intra-site variation and maximizes the inter-site variation in soil samples. Using these three size fractions in comparing soils enabled 87.9% of soil samples to be discriminated in their study. The particle size fractions used in this study (<41 μm, 60-41 μm, 130-60 μm, and >130 μm) provide slightly more detail on the intermediate size fraction, but closely follow those of Sugita and Marumo. The size fractions used in this study allow us to discriminate 94% of the inter-site undisturbed soil samples. All three locations are significantly different from each other with respect to particle size distribution for each particle size fraction except for one: Rock Creek Park-

Marvin Gaye Park (RCP-MGP) in the 130-60 μm fraction (Table 7). These comparisons were made using ANOVA, following Equations 10-14.

Chazottes et al. (2004) compared the particle size distributions of control soil samples with those collected from boots, athletic shoes, and tissues (transfer soil samples). Two soils were used in this study, one rich in “medium” particles (1,000-63 μm), and one with a bimodal particle size distribution. From their data, they concluded that there was a common pattern between the two soils: when comparing the control and transferred soil, there were significant differences found in the “extreme” size fractions (>1,000-4,000 μm and < 20 μm), with the size fractions in between unaffected. However, when comparing the control sample to transferred soil samples from different locations, all size fractions were significantly different. This is in contrast to the results from this study, where significant differences were found in all size fractions even when comparing the control soil with the “correct” transferred soil.

The Chazottes et al. study did not account for the effect of soil moisture; the authors only state that, “at each site, the soil was watered to ensure sufficient size of suspect sample.” In this study soil moisture was measured to determine whether the amount of accumulated soil material and the resultant particle size distribution was affected by soil moisture content. By not making note of the soil moisture content for their experiments, the Chazottes et al. group has made it difficult for other studies to compare the results of their work.

Croft and Pye (2004a) studied soil transfer behavior between soils and different shoe types. Using ANOVA at the 95% confidence level, they found that the clay fraction (< 2 μm) was reduced in the transferred soil samples compared to the control samples for all of the shoe types used (boots and athletic shoes), with the silt and sand fractions showing no significant difference. Croft and Pye found a high degree of agreement between the percentages of both silt and sand size fractions for the soil control sample and the transferred samples. In this study, there were significant differences found in the silt and sand fractions between the control and transferred soil samples.

The sampling depth used in the Croft and Pye study was 0-5 cm below the surface, and the transfer portion of their study was conducted in the laboratory after the collected soil had been homogenized; this may be the fundamental difference between the present study and Croft and Pye, namely, that our samples were collected in-situ in the field, and Croft and Pye used a laboratory homogenized sample. This may be why a smaller proportion of matches were found in my study. Further, in Croft and Pye, the soil was walked on for three minutes, a time period that is longer than used in this study.

Soil Color Measurements

The only statistically significant soil color differences at the Rock Creek Park location were in the undisturbed soil samples. This is likely due to the abundance of large (1 to 3 cm) pieces of gravel present at the location. The cobbles take up a large portion of the colorimeter analysis area and vary in color between samples even though their mineralogy may be similar (milky quartz, iron-stained quartz, etc.). None of the individual size fractions were determined to have significantly different colors.

In contrast to the Rock Creek Park location, half of the size fractions have been determined to be significantly different at the Sherman Circle location. These include the > 130 µm and < 41 µm size fractions. This could be due to the non-uniform soil types seen at this location, ranging from curbside debris to soil samples underneath tree canopies. At each location, samples were collected with the intent of capturing the maximum variability in soil properties; in forensic analyses, this variation in soil color may not be present, depending on the sampling method.

Interestingly, neither location showed significant variation of soil color in the 130-60 µm or 60-41 µm size fractions. This further confirms the validity of the decision to recommend the 130-60 µm size fraction for heavy mineral analysis and other tests; if there is consistently no significant variation of color among samples from a given site, in this particular size range, it is likely the most robust for forensic analyses.

At the moderately-to-heavily vegetated locations (Sherman Circle and Marvin Gaye Park), an observed phenomenon occurred that is commonly referred to as "grass washing". Grass washing is the act of grass and/or other material such as fallen leaves sweeping away soil material from the shoes as an individual moves across the area. Initially, soil material accumulates on the shoes, but with further steps, the blades of grass sweep away a large portion of the soil material. In some cases, this resulted in a very small (0.1 g) amount of soil material adhering to the shoes, rendering a sample unavailable for digital color analysis (as stated above, the lower limit has been observed to be 0.5 g of soil material). Grass washing may be affected by many factors, including soil moisture, moisture adhering to the grass/leaves, and height of vegetation.

The findings in this study that soil color changes upon sieving are consistent with those of Croft and Pye (2004b). Their study utilized similar size fractions (150-63μm compared to 130-60 μm; 63-20 μm compared to 60-41 μm), and found that the sieved portions of soil were different from the whole, unsieved soil, with the L* value most significantly affected, and the a* and b* values not as affected in most of the soils. From their findings, Croft and Pye determined that because soil color changes upon sieving, the same size fraction should be used when comparing soil samples, which the findings from this study confirm.

Croft and Pye (2004a) compared soil color from control samples with soil that had been transferred to shoes. Using ANOVA at the 95% confidence level, they found no significant difference in the L*, a*, or b* values between the control and transferred soil samples for any of the four types of soil or 5 types of shoes used in their study. The procedures that Croft and Pye used for quantitatively determining the color of the soil were different from those of the present study; for each soil sample, Croft and Pye took the entire < 150 μm fraction, ground it to a < 10 μm powder, and then measured color. In this study, I attempted to evaluate whether obtaining color measurements for each of the chosen particle size fractions would yield as good a result. In this study, poorer agreement was found between the color measurements of individual size fractions compared to the method of Croft and Pye. However, because their data shows a good relationship between control soil and transferred soil color, the method employed by Croft and Pye may be the best for forensic analyses.

Sugita and Marumo (1996) attempted to compare soil color for sample discrimination using 73 soil samples from three types of soil. They found that about 70% of soil samples could be discriminated based on the soil color of air-dried soil alone. Our results agree with those of Sugita and Marumo: when performing inter-sample color comparisons, 94% of undisturbed soil samples could be discriminated (Table 10). The only soil sample pair that could not be discriminated was the RCP-MGP undisturbed, unsieved fraction. However, it should be noted that any intra-site variation in soil color may complicate the interpretation of the results; a greater amount of intra-site variation affects the ability to compare soil samples from other locations.

Heavy Mineral Analysis

Although the presence of iron oxide spheres was not determined to be a characteristic feature for the sample sites, the abundance of these particles may aid in provenance analysis. A search of the literature revealed that similar textures seen in the iron oxide particles collected as part of this study are characteristic products of the coal combustion process. These iron oxide spheres are found in all metropolitan areas where this process occurred (Locke and Bertine, 1986). The District of Columbia currently has one fossil fuel burning power plant in operation, the Capitol Power plant located in Southeast D.C. The Capitol Power Plant has been in operation since 1910. The proximity of the three sample locations in this study to the Capitol Power plant may shed insight to the abundance and characteristics of the iron oxide spheres found at each location. Decreasing order of both abundance and size of these iron oxide spheres according to location is: Marvin Gaye Park → Sherman Circle → Rock Creek Park, following their respective increasing distance from the power plant. The Capitol Power Plant is responsible for the emission of 65% and 46% of particulate matter that are < 2.5 μm and 2.5 μm -10 μm, respectively (Metropolitan Washington Air Quality Committee, 2002). Although there is no documentation regarding particulate matter >10 μm from the Capitol Power Plant, it is reasonable to infer that it is the source of many of the iron oxide spheres found in the soil samples.

The spheres appear in all locations from this study but have a variety of textures: smooth (RCP), myrmekitic (RCP), micrographic (SHC), cracked (MGP), blocky (MGP) and dendritic (RCP/SHC/MGP) (Figures 42-43, Appendix 8). An explanation of these textures can be found in Table 16. Although only a limited number of samples were examined, some of these textures may be diagnostic of certain soils.

Texture	Description	Image Reference
Myrmekitic	Wormy appearance; long, rounded segments.	Appendix 8
Micrographic	Angular intergrowths, usually as a result of supercooling of a crystallizing melt.	Figure 42
Cracked	Akin to mudcracks.	Appendix 8
Blocky	Squared-off segments across mineral surface.	Appendix 8
Dendritic	Feathery crystals, commonly produced during crystallization when high growth rates are produced by supercooling, or other type of saturation.	Figure 43; Appendix 8

Table 16 Description of surficial textures observed in iron oxide spheres.

There are rarely a sufficient number of grains in the heavy mineral fraction of a test or evidentiary sample to perform a statistically significant mineral count (Palenik, 2007). Characterization of this fraction is commonly performed by recording the mineral phases seen in a sample. A common approach in asserting if two samples are derived from the same source is to identify the heavy mineral phases in one sample and determine if all are present in the second sample (Palenik, 2007).

The magnetic mineral fractions were collected with a neodymium magnet. The magnet was placed in a sealed Ziploc® bag, which was itself placed in another Ziploc® bag that had been turned inside out. The bags were placed on the soil surface and immediately lifted. The bag with the magnet was then removed from the second Ziploc®, which was subsequently turned right-side out to contain the newly collected magnetic fraction. There was a large amount of magnetic material at Rock Creek Park, and significantly less at Sherman Circle, and even less at Marvin Gaye Park. The amount of magnetic material varied greatly among the locations, and could in principle, be quantified. At Rock Creek Park, there was an abundance of magnetic minerals ranging from euhedral octahedrons to anhedral grains. At Sherman Circle, octahedrons were also found, though, not in as high a fraction as Rock Creek Park. The magnetic mineral fraction overwhelmingly exceeded the proportion of magnetic spheres at RCP. At Marvin Gaye Park, the magnetic minerals are dominantly anhedral, and metal spheres make up a significantly larger fraction than at the other two sites. The anecdotal hypothesis that the ratio of magnetic spheres to magnetic minerals decreases in the sequence Marvin Gaye Park → Sherman Circle → Rock Creek Park should be tested by quantitative means in a future study.

XRD Patterns

X-ray diffraction data are useful for comparing bulk soil mineralogy among the different locations. Mineral assemblages characteristic of each location can be useful in sample comparison. Both the determination of the dominant minerals present in a given soil, as well as the mineralogy of both the heavy mineral fraction and the magnetic mineral fractions, can be useful in characterizing the mineral assemblages. Mineral texture and morphology can also contribute to the identification of soil samples.

However, due to the limited amount of material yielded from the transfer portion of the study, we were unable to use this method for comparing mineralogy for comparing bulk soil samples with their respective transferred soil material samples. This is most apparent in the samples from Marvin Gaye Park, where 56% of transferred soil samples do not meet the ideal mass requirement and 39% of samples do not meet the minimum mass requirement for XRD analysis. Half of the transferred soil samples from Rock Creek Park would not meet the ideal soil mass requirement and 22% would not meet the minimum sample mass requirement (Dr. P. Zavalij, University of Maryland X-ray Crystallographic Center, Personal Communication).

Analyzing the XRD patterns presents a set of challenges. Certain minerals are prone to higher levels of variability within their structure: many of the clay minerals, including vermiculite, montmorillonite, and chlorite can vary significantly with respect to mineral composition. Other minerals, such as the micas, illite, and serpentine have a moderate level of variability within their structures. Minerals such as quartz and kaolinite do not contain much element substitution in their structure, and therefore the variability is relatively low. Minerals with a higher level of variability within their structure tend to have peaks with variable position on the XRD pattern. In addition to element variability, polymorphs of minerals can cause peaks to shift slightly For example, antigorite, lizardite, and chrysotile, members of the serpentine mineral group, have slightly different 2θ values. The different proportions of these minerals present within a sample can cause slight variations in peak position between XRD patterns from samples of the same location. The peak at 4.9 and 4.4 Å (2θ= 18 and 19.9 degrees) are due to muscovite. At these two values, there is a small, but clear peak in Sherman Circle, and a smaller peak at Marvin Gaye Park, but does not rise above background at Rock Creek Park. The serpentine peak at 3.6 Å (2θ = 24.6 degrees) is also very clear in the Rock Creek Park and Sherman Circle patterns, but nonexistent in the Marvin Gaye Park pattern. Quartz is apparent at all three locations, but is most pronounced relative to other peaks at Marvin Gaye Park. The peaks near 7 Å are a combination of serpentine and chlorite. The tentative explanation for the shape of the peaks is that the higher d-spacing portion of the peak is serpentine, and the lower d-spacing portion represents chlorite. In the Rock Creek Park sample, the main portion of the peak is due to serpentine, with a chlorite shoulder. This relationship is reversed for the Sherman Circle sample, where the main part of the peak represents chlorite, with a possible serpentine shoulder. This relationship may be diagnostic for these localities, and this hypothesis should be examined in further studies.

The most important minerals from the three localities include chlorite, serpentine, muscovite and quartz. All samples exhibited prominent quartz peaks when examined by x-ray diffraction of the undisturbed soil. In addition to quartz, Rock Creek Park was characterized by a peak near 7 Å (2θ =12.3 degrees) with a shoulder on the high 2θ side, that is probably a composite serpentine-chlorite peak. Muscovite is a minor component, if present. The magnetic fraction for Rock Creek Park was quite massive. Magnetic minerals, dominated by magnetite, made up the largest proportion of this sample. Metal spheres were also present, but were subordinate. These features are characteristic of the Rock Creek Park samples that formed part of this study. The XRD patterns of the Sherman Circle samples contain, in addition to quartz, significant muscovite and chlorite. The magnetic fraction is much smaller at Sherman Circle, and contains some euhedral magnetite as well as metal spheres. The mineralogy of the samples from Marvin Gaye Park is dominated by quartz, with minor peaks indicating some muscovite and chlorite. The magnetic fraction is minor, but exhibits the highest proportion of metal spheres to magnetic minerals. Finally, it is important to keep in mind that the XRD patterns are only showing the major (>5%) mineral phases present within a sample. Minor, or trace, mineral phases, which often provide the distinguishing features that are valued in forensic analyses, are not well represented in the XRD patterns.

Chapter 8: Conclusions

The goal of this study was to advance our understanding of soil and anthropogenic material transfer behavior in an urban environment for the improvement of forensic analyses. The principal objective was to determine whether there was a preferential transfer of soil and urban material to shoes according to the tread distribution, and if the transfer affected the characteristics of the soil material. This phenomenon was studied by characterizing undisturbed soil samples according to their color, particle size distribution, and mineralogy. These characteristics were then compared to soil material that had been recovered from the shoes to determine the presence and extent of these differences.

It is clear that there is a fractionation of particle size as a result of transfer of material from soils to shoes; however, there is no consistent pattern between enrichment or depletion of a particular size fraction with soil moisture content or walking versus jogging. There was a large range in the percentage of enrichment and reduction in the transferred soil samples with respect to the undisturbed soil. The maximum amount of fractionation occurred with a sample from Marvin Gaye Park for Transfer 1, for the RealFlex Jogging trial (MGP RFJ 1) in the 60-41 micron size fraction: this sample exhibited a 4.5-fold increase in the proportion of this size fraction compared to the undisturbed soil. The greatest reduction in the proportion of a given size fraction also involved transfer at Marvin Gaye Park; Nike Walk from Transfer 2 in the <41 micron size fraction, exhibited a 58% reduction compared to the undisturbed soil. The findings suggest that the percentage of shoe tread making up the shoe sole, and the tread size distribution may contribute to the amount of soil material that accumulates on the shoe; however, it is uncertain whether or not this characteristic affects the particle size and mineralogy of the soil material that accumulates. For example, the Reebok Zignano, with the largest amount of tread gap, transferred the largest number of soil samples that did not have enough mass to take color measurements from (Figure 20, Table 3). Additionally, even though the Reebok RealFlex and Nike Air Pegasus are comparable in terms of tread and tread gap distribution (37% and 33% tread gap and 63% and 67% tread, respectively), the Nike Air Pegasus had 10 of 18 soil samples that did not yield enough material for color measurements whereas the Reebok RealFlex only had 7 of the 18 samples not meet this condition. The increase in the number of samples with low mass from the Nike Air Pegasus is likely due to the large concave structure in the heel, a "concentrated tread gap" area on the shoe. The aforementioned observations indicate that multiple shoe characteristics are factors that can have a large influence on the amount, and possibly the characteristics, of the resultant transferred soil. Due to the variable results, further study is needed to assess each individual factor more closely.

The results indicate that the soil color analytical technique employed in this study is not reliable for comparing undisturbed soil samples from different locations as well as undisturbed soil samples with their respective transferred soil samples. The intra-site variation in soil color was significant in many of the size fractions and affected all three locations. In many cases, there was not enough soil material collected from the shoe to obtain color measurements; therefore, the author concludes that transferred soil material should only use color as a comparing characteristic when analyzing the unsieved portion. It should be noted that transferred soil samples possess higher L* and b* values compared to the undisturbed soil samples, but samples from different locations still fell within organized “clusters” with minimal overlap.

The x-ray diffraction data helps to further enhance sample identification in this same manner because XRD patterns are akin to location “fingerprints”. In forensic analyses, these fingerprints aid in assessing the likeliness of two samples sharing a source. Creek Park, Sherman Circle, and Marvin Gaye Park all have distinct x-ray diffraction patterns. These XRD patterns can be used as location fingerprints, where comparisons of mineralogy presence and intensity can be made. For the most accurate comparison, it is recommended that soil samples of similar size fractions be submitted to minimize larger mineral grain biases in the XRD pattern. The challenge presented with this type of analysis lies with the potential low sample yield from shoes. The total amount of recovered soil material transferred to the shoe may meet or exceed the mass requirement for XRD analysis, however, after the sample has been sieved to an equal size fraction of a comparison soil sample, it may fall below this requirement. Although XRD analyses may not be useful in all forensic investigations, such as comparing samples with low (< 0.5 g) mass, when applicable, this type of analysis can be used in bulk soil mineralogy comparison.

XRD analysis can be combined with heavy mineral and magnetic fraction analysis to further discriminate two given locations. The most important minerals from the three localities include chlorite, serpentine, muscovite and quartz. Rock Creek Park was characterized by quartz and the composite chlorite-serpentine peak. Muscovite is minor, and the magnetic fraction was massive, with minor metal spheres. Sherman Circle is characterized by quartz, with significant muscovite and chlorite. The magnetic fraction is modest in size. Marvin Gaye Park is dominated by quartz, with a minor peaks indicating some muscovite and chlorite. The magnetic fraction is minor, but exhibits the highest proportion of metal spheres to magnetic minerals.

Particle size distributions can be used in conjunction with the mineralogical analyses to further validate whether two samples do or do not come from the same location. For example, the results of this study confirm that a fractionation of particle size occurs with the soil transfer process. Based on the type of soil being compared, it can be determined if relative enrichments or depletions in certain particle size fractions are consistent with the expected partitioning resulting from the transfer of soil from ground to shoe. Used in combination, the analytical techniques presented in this study provide a powerful means for determining whether two given soil samples are derived from the same location.

There are many procedures for analyzing soil samples in forensic laboratories. With more research that is dedicated to observing how shoe tread percentage and shoe tread distributions accumulate soil, and the statistical analysis of how these characteristics compare, forensic analyses can be improved to the point of being as ubiquitous and as respected as other forms of evidence (e.g. DNA evidence).

Appendix 1: Soil Mineralogy

Silicates

Silicates are minerals that contain silica tetrahedra as part of their structure. Most of the important primary soil minerals are silicates, including quartz, feldspars, micas, pyroxenes, and amphiboles. The primary silicate minerals dominate the majority of the sand and silt fractions in soils, with the relative abundance of each depending on parent material composition and the extent of weathering. Secondary silicate minerals such as kaolinite and smectite form by the weathering of primary silicates and are common soil minerals in the fine silt and clay fractions. Silicate minerals are categorized according to their structure and include the nesosilicate, sorocilicate, cyclosilicate, inosilicate, tectosilicate, and phyllosilicate groups.

Nesosilicates, sorosilicates, and cyclosilicates

Silicate minerals that consist of independent silica tetrahedra are known as nesosilicates or orthosilicates. Olivine ($(Mg,Fe)SiO_4$) is a common nesosilicate in which adjacent silica tetrahedra are held together by the electrostatic attraction between silica tetrahedra and interstitial Mg^{2+} or Fe^{2+} cations. Olivine is susceptible to weathering, and therefore, is not a common mineral in mature soils. Sorosilicates such as clinozoisite ($Ca_2Al_3OOHSiO_4Si_2O_7$) contain pairs of tetrahedra that share one corner O atom. Cyclosilicates have six tetrahedra arranged in a ring, each sharing two corner O atoms. Sorosilicates, along with cyclosilicates such as beryl ($Be_3Al_2(SiO_3)_6$) and tourmaline are resistant to weathering, making them common accessory minerals in soil. The bonding between silica tetrahedra in the soro- and cyclosilicate groups creates a stronger mineral structure, forming a more resistant mineral.

Inosilicates

The inosilicate (chain silicate) group includes pyroxenes and amphiboles, which originate in mafic and intermediate rocks. Chain silicate minerals are categorized into single- and double- chain silicates. Single-chain silicates such as pyroxenes have long chains of silica tetrahedra that share two corner O^{2-} ions. Double-chain silicates such as amphiboles are composed of parallel chains of silica tetrahedra; this provides for greater resistance to weathering than the single-chain minerals. Double-chain silicates are more resistant to weathering than single-chain silicates, but less so than tectosilicates (Allen and Hajek, 1989).

Tectosilicates

Quartz is the most common tectosilicate and is also the second most abundant mineral in the earth's crust, second only to feldspars (Allen and Hajek, 1989). The silica tetrahedra are each bonded to four other tetrahedra; all O^{2-} anions in each tetrahedron are shared between two tetrahedra to give a three-dimensional network of silica tetrahedra. Minerals with a three-dimensional structure have no planes of weakness and are resistant to both physical and chemical weathering.

Feldspars are tectosilicates in which one to two out of every four Si^{4+} ions are substituted by Al^{3+}. This substitution creates a net negative charge which is balanced by a cation (e.g. Ca^{2+}, Na^{+}, or K^{+}) that resides between the silica tetrahedra. Feldspars in which Ca^{2+} or Na^{+} balance the negative structural charge are known as plagioclases. The plagioclase series includes two end members – one in which 100% of the charge is satisfied by Ca^{2+} cations (anorthite) and one in which 100% of the charge is satisfied by Na^{+} (albite). Plagioclases that contain more sodium than calcium are more resistant to weathering. Because of the aluminum substitution and interstitial cations, feldspars are more susceptible to weathering than quartz.

Zeolites are tectosilicates that have a less uniform structure than quartz or feldspars. In the zeolite structure, silica tetrahedra are linked to form open structures with more interstitial space than feldspars. Like feldspars, zeolites have Al^{3+} substitution for some of the Si^{4+}, which produces a negative structural charge that is balanced by an interstitial cation. Zeolites can form in basalts and other mafic igneous rocks, and can be found in a wide range of soil environments (Ming and Mumpton, 1989).

Phyllosilicates

Phyllosilicates (layer silicates) contain silica tetrahedra in which all three O^{2-} ions at the base of each silica tetrahedron are shared between two other tetrahedra, and the linked tetrahedra are arranged to form a sheet of hexagonal rings, called the tetrahedral sheet. The apical O^{2-} ions of each tetrahedron are shared or bonded to a metal hydroxide octahedral sheet. This can be seen using the mineral gibbsite ($Al(OH)_3$) as an example. Combining an $Si_2O_5^{2-}$ silica tetrahedral sheet with an $Al(OH)_3$ octahedral sheet creates a mineral with the formula $Al_2Si_2O_5(OH)_4$ - kaolinite. Phyllosilicates where one silica tetrahedral sheet is bonded to one octahedral sheet are called 1:1 phyllosilicates. Kaolinite and serpentine are examples of 1:1 layer silicates.

In the 2:1 layer silicate structure, an octahedral sheets are present between two tetrahedral sheets. A 2:1 layer that contains two $Si_2O_5^{2-}$ tetrahedral sheets sandwiching an $Al(OH)_3$ or $Mg(OH)_2$ octahedral sheet. The formulas of 2:1

phyllosilicates have twice as many Si tetrahedra and only half as many OH groups per unit cell compared with the formula of 1:1 layer silicates because the octahedral sheet is shared between two different tetrahedral sheets. The type of layer (1:1 or 2:1) is the primary criterion for classifying phyllosilicates.

1:1 Layer Silicates

The kaolin and serpentine groups are included in the 1:1 layer silicates. The kaolin group comprises dioctahedral minerals in which Al^{3+} is the cation and includes the minerals kaolinite, halloysite, and nacrite which all have the formula $Al_2Si_2O_5(OH)_4$. The three kaolin minerals differ in the stacking arrangement of the surrounding 1:1 layers (Bailey, 1980). Halloysite and nacrite form in hydrothermal environments and are not stable in soils. Kaolinite is very common in soils, and can either have a hydrothermal origin or can be pedogenic (formed in the soil). Kaolinite forms from the weathering of other aluminosilicates in soils where silica and relatively mobile base cations such as Ca^{2+} and Mg^{2+} have been leached (Dixon and Weed, 1989).

The serpentine group comprises trioctahedral 1:1 silicates that usually have Mg^{2+} or Fe^{2+} in the octahedral sheet, although Co, Cr, Ni, and Al also can substitute. The serpentine minerals are found in soils derived from ultramafic rocks (serpentinites) that originate in the oceanic crust. Serpentinites form by hydrothermal alteration of olivine, pyroxene, and peridotite, and are also found in ultramafic metamorphic rocks. Magnetite commonly forms concomitantly with serpentine from these ultramafic rocks (Sleep et al., 2004). Serpentines weather easily, making them uncommon in the fine fractions except in very young soils. As a result of weathering, serpentine-derived soils tend to be high in pedogenic chlorite, which is normally an unstable clay mineral, smectite, and talc (Wildman et al., 1968; Parisio, 1981). When iron is present in the serpentine structure, goethite and other iron minerals and mineraloids are common alteration products (Schaetzl and Anderson, 2005).

2:1 Layer Silicates

All 2:1 phyllosilicates contain two $Si_2O_5^-$ tetrahedral sheets that share apical O atoms with either a dioctahedral sheet (containing Al^{3+} or Fe^{3+}) or a trioctahedral sheet (containing Mg^{2+} or Fe^{2+}). The 2:1 phyllosilicates are classified according to their layer charge (the net charge on the 2:1 layer caused by isomorphous substitution) and on whether isomorphous substitution occurs in the tetrahedral sheet (Al^{3+} substituting for Si^{4+}) or in the octahedral sheet.

Talc and pyrophyllite are the simplest 2:1 clay minerals in terms of chemical composition, because they have no isomorphous substitution in either the tetrahedral or octahedral sheet. Pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) has an $Al(OH)_3$ dioctahedral sheet; talc is trioctahedral and has an $Mg(OH)_2$ octahedral sheet ($Mg_3Si_4O_{10}(OH)_2$). Talc and pyrophyllite may form from ultramafic parent material in hydrothermal and low-grade metamorphic environments; they also form in soils from weathering of pyroxenes and amphiboles (Zelazny and White, 1989; Schulze, 2002).

Micas are primary 2:1 layer silicates found in many soil environments. Muscovite, the most common soil mica, contains an $Al(OH)_3$ dioctahedral sheet. Biotite is the second most common soil mica, and can be a common mineral in soils derived from mafic parent material. Like muscovite, biotite has a layer charge of 1.0 cause by Al^{3+} substituting for Si^{4+} in the tetrahedral sheet. Biotite differs from muscovite by having a trioctahedral sheet in which the Fe^{2+} is the dominant octahedral cation. The Fe^{2+} gives biotite a darker color than muscovite, and also causes biotite to weather more easily.

Micas in soils are primary minerals that are inherited via physical weathering of the parent material. Muscovite is found in granitic igneous rocks as well as in metamorphic rocks from medium and high-grade metamorphism. Biotite can weather up to 100x more rapidly than muscovite and is less common in soils. The difference in weathering rates can be attributed to different weathering mechanisms within the minerals' structure. In muscovite, the primary weathering mechanism is the loss of an interlayer K^+ cation. In biotite, electrostatic repulsion between interlayer K^+ and the OH^- groups of the trioctahedral sheet increases the rate of weathering. Similarly, the oxidation of Fe^{2+} to Fe^{3+} increases weathering in biotite (Schaetzl and Anderson, 2010). Illite and glauconite are clay-sized micas common in moderate-to-highly weathered soils. Micas may weather to other minerals such as vermiculite and smectite (Schulze, 2002).

Vermiculites form almost exclusively from the weathering of micas and chlorites. This occurs by replacement of potassium in the interlayer sites with hydrated cations (such as iron and magnesium), (Schulze, 2002).Vermiculites are easily weatherable, and therefore, are generally only seen in young soils (Kittrick, 1973).

Smectites form in soils rich in silica, magesium, and calcium.These ions are found in poorly drained environments and in low-leaching environments (Folkoff and Meentemeyer, 1985). Most smectite is pedogenic, and is most abundant in the clay fraction. Smectites form by the partial weathering of other 2:1 clays such as mica, vermiculite, and chlorite. Montmorillonite is a smectite that is common in poorly drained or dry soils derived from magnesium-rich imtermediate and mafic rocks.

Illites are a major component of the fine grain fraction in soils. These minerals form by the weathering of silicates such as feldspars and micas when potassium and aluminum have been leached from their structures (Meunier and Velde, 2004). When potassium is leached from illite's structure, it weathers into other minerals such as vermiculites and smectites. Although considered to be an unstable soil mineral, illite is commonly seen in large quantities in the clay fraction of soil (Meunier and Velde, 2004).

Metal Oxides, Hydroxides,and Oxyhydroxides

Metal oxides, hydroxides, and oxyhydroxides are secondary minerals and mineraloids that are ubiquitous in soils. Secondary iron and aluminum oxides are major components of the clay fraction of highly weathered soils. In younger soils, these are typically present as coatings on mineral grains, where they influence aggregation and retention of certain ions (Hsu, 1989). The most common are aluminum-, iron-, titanium-, and manganese oxides.The most abundant aluminum oxide in soils is gibbsite ($Al(OH)_3$) (Shaetzl and Anderson, 2005).

Iron oxides are more abundant in soils than aluminum oxides. The type of iron oxide present depends on the weathering environment. Iron oxides form when Fe^{2+} in primary minerals is oxidized, released from the mineral structure, and re-forms as an iron oxide mineral. Iron oxides can occur both as coatings on mineral grains in mild and moderate weathering environments and as distinct particles in severe weathering environments (Schwertmann and Taylor, 1989). Due to iron oxides having a high area:volume ratio, even a small amount of iron oxide can greatly enhance aggregation and affect soil color. Goethite (FeOOH) is the most common iron oxide mineral in soils and imparts a brown to yellowish-brown color in soils. Goethite particles are small (< 0.1 µm). Hematite (Fe_2O_3) is usually found along with goethite; it forms in highly-weathered soils but it can also be inherited from the parent material (Schulze, 2002). Even a small amount of hematite will give soil a strong, blood-red color. Magnetite (Fe_3O_4) is a primary mineral inherited from the parent material; it can be found as black, magnetic particles in the coarse fraction of many soils. Magnetite and its weathering product, maghemite, are found mainly in soils derived from basalt or other mafic igneous rocks (Allen and Hajek, 1989; Schaetzl and Anderson, 2010).

Rutile and ilmenite are titanium oxide minerals that occur in soils predominantly as primary minerals inherited from igneous rocks. The polymorph of rutile, anatase, is less common in soils (Schulze, 2002).

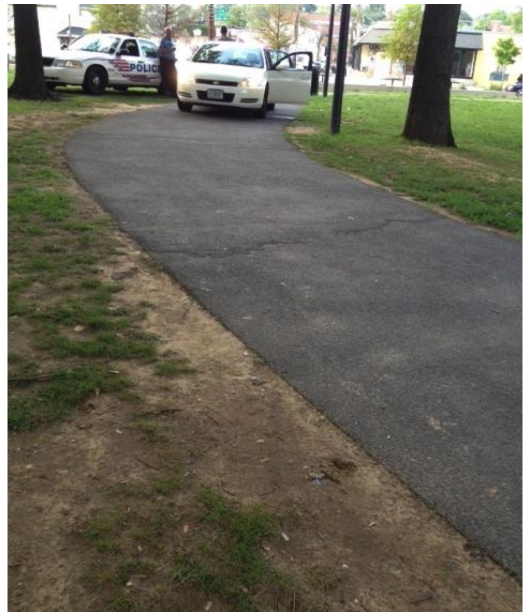
Chloride, Sulfides, Sulfates, and Carbonates

Chlorides (NaCl, KCl) are extremely soluble and occur mainly as salt crusts on the surface of arid soils, such as soils derived from saline parent material or largely influenced by saline waters (Doner and Lynn, 1989). Carbonates ($CaCO_3$ or $CaMg(CO_3)_2$) are less soluble than chlorides, but are still typically found only in dry or young soils or in soils with calcareous parent material.

Sulfates are relatively soluble and occur predominantly in dry regions. Gypsum ($CaSO_4•2H_2O$) is the most common sulfate mineral in dry soils and can either be inherited or pedogenic. In contrast, jarosite ($KFe_3(OH)_6 (SO_4)_2$) forms in acidic environments where FeS_2 from pyrite or mine spoils is exposed to air and oxidized. The presence of jarosite gives soil a yellow-brown color. Pyrite (FeS_2) is the most common sulfide mineral in soils and is rapidly oxidized when exposed to air or oxygen-rich water (Doner and Lynn, 1989).

Appendix 2: Additional Soil Sample Location Pictures

Left: Photos from the Rock Creek Park sample location. Top: Close-up of a Rock Creek Park sample before (above left) and after (above right) collection.



Marvin Gaye Park sample pictures. Clockwise from above left: urban soil material located at park bench; after sample collection area next to walkway; field of view showing location variability.

Appendix 3: Particle Size Distribution Bin Justification

The sizes used for sieving used in this study are (in μm) > 130, 130-63, 63-41, and < 41. These fractions allow for a detailed analysis of the sand fraction (medium, fine, very fine sand) as well as information on a combined silt and clay fraction of soil samples. The <150 μm fraction contains the most useful portion of the soil sample for forensic purposes (#2, 4, 7 in list below), so there is a limited need for the >150 μm fraction. 63 μm is a commonly used end member for particle size bins (#3, 4, 9, 10 in list), which is the lowest bin used in this study. The 130-63 μm fraction was chosen for the heavy mineral analysis based on the findings on Junger and Palenik (#3 and 6 in list).

This study is using particle size distribution as one criterion for discrimination. Considering constraints associated with this study (time, money), and referencing published work, the chosen 4 bins are appropriate for obtaining useful information on particle size distribution while also being appropriate for further analyses (heavy minerals).

1. Chazottes et al. (2004): Particle size analysis of soils under simulated scene of crime conditions: the interest of multivariate analyses

- Sieving sizes (μm): 4000, 2000, 1000, 500, 250, 125, 63, 50, 20 (French AFNOR sizes)

2. Croft and Pye (2004a): Multi-technique comparison of source and primary transfer soil samples: an experimental investigation

- Sieving sizes: Laser diffraction (logarithmic curve ranging from 0.04 to 2,000 μm)
- Previous studies showed the <150 μm fraction showed the highest amount of discrimination between samples

3. Junger (1996): Assessing the unique characteristics of close-proximity soils: Just how useful is soil evidence?

- Sieve sizes (μm): 1,000, 850, 500, 425, 250, 150, 125, 63 (recognized standards used by the USGS)
- Planned mineralogical analysis on the 125-63 μm fraction

4. Guedes et al. (2009) Quantitative colour analysis of beach and dune sediments for forensic applications: A Portuguese example

- Sieving sizes (μm): < 150, < 63
- The dried, sieved <150 fraction provided for the best discrimination between samples

5. Morgan and Bull (2007a) The use of grain size distribution analysis of sediments and soils in forensic enquiry

- Obtained particle size distributions using a laser granulometer, not by manual sieving.

6. Palenik (2007): Heavy minerals in forensic science

- Separating sediment into size fractions for the subsequent concentrating of specific elements is in most cases a more valuable use of time than obtaining highly accurate particle size distributions
- Heavy mineral fraction 180-90 μm and < 90 μm
- The above fractions normally contain the majority of the heavy mineral suite and the majority of the soil fraction that adheres to clothing

7. Pye et al. (2006): Discrimination between sediment and soil samples for forensic purposes using elemental data: an investigation of particle size effects

- Sizes (μm): <150, 150-63, 63-20, < 20
- < 150 μm provided best compromise between sample size comparison and data resolution

8. Rawlins et al. (2006): Potentials and pitfalls in establishing the provenance of earth-related samples in forensic investigations

- < 125 μm → for clay analysis, further sieved to <63 μm and let settle to isolate the <2 μm fraction

9. Sugita and Marumo (2001): Screening of soil evidence by a combination of simple techniques: validity of particle size distribution

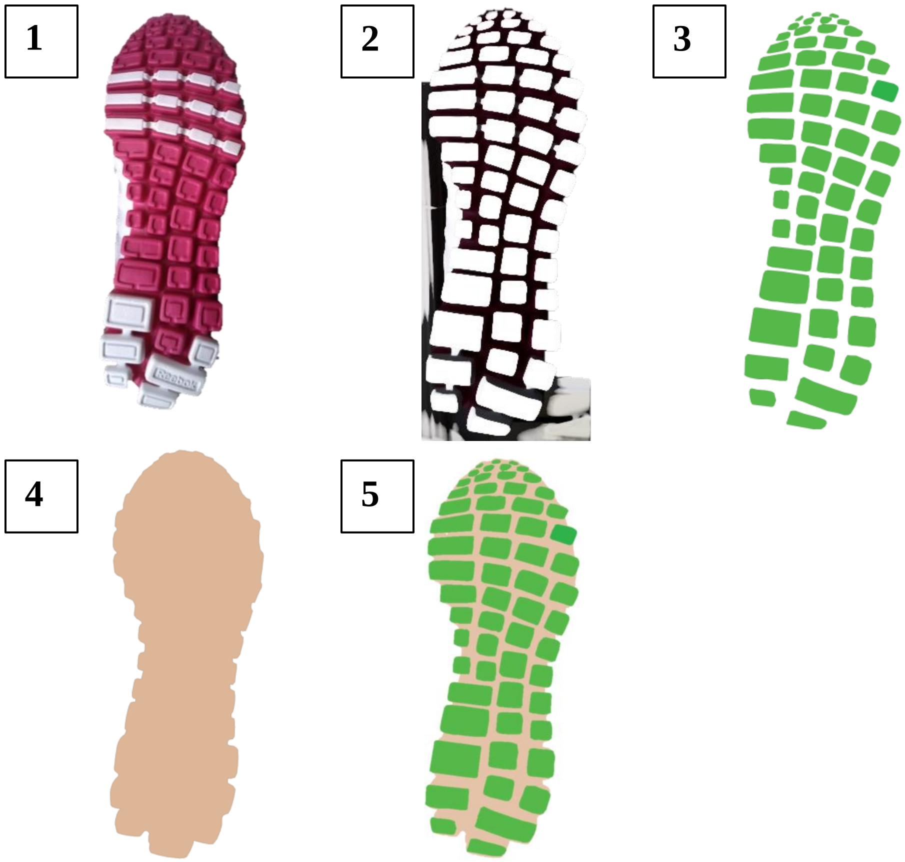
- Sieving sizes (μm): < 50, 50-200, 200-2,000

- Original sizes were (μm): < 50, 50-100, 100-150, 150-200, 200-1,000, 1,000-2,000, but there was a large amount of variation (CV 7-103%), so they combined groups into the above bins which reduced variation (CV <10 %)

10. Wanogho et al. (1989): Determination of particle size distribution of soils in forensic science using classical and modern instrumental methods

- Sieving sizes (μm): 2,000, 1,000, 500, 250, 90, 63

Appendix 4: Image J Procedure for Mapping Shoe Tread



1: After the shoe is digitally photographed on an even, horizontal surface, the image is imported into the ImageJ program. Any background in the image should be removed.

2: Outline all potential contact surface areas on the shoe sole (the treads; white boxes). Image can be zoomed in to desired magnification for detailed outlining.

3: The treads are then assigned a color, and the remainder of the shoe is removed using the threshold function. Measure the total area.

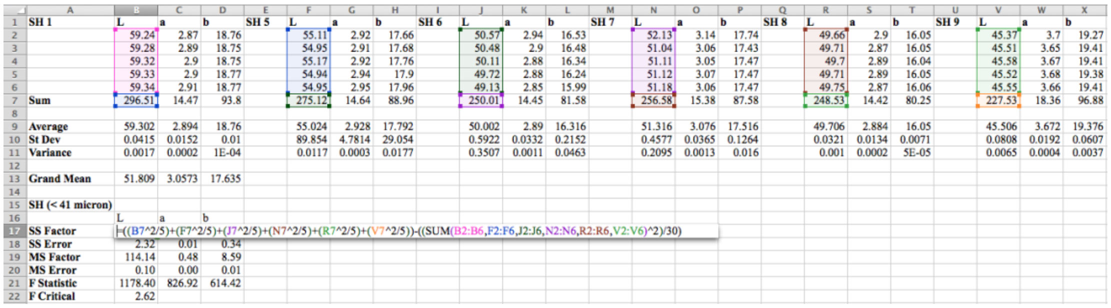
4: Keeping the previous window open, open a second image of the shoe (step 1) and outline the entire shoe sole. Assign this shape a second, contrasting color. Measure the total area.

5: Transpose the image from step 3 onto image 4. Shoes can be characterized as either a percent of the areas of image 3 over image 4; or, can be expressed as numerical values. Refer to Figure 20 for the tread and tread gap statistics of the shoes used in this study.

*Note: ImageJ is a free, public-access program available from the National Institutes of Health (NIH). Download is available from http://rsb.info.nih.gov/ij/.

Appendix 5: Analysis of Variance (ANOVA) Example Calculations

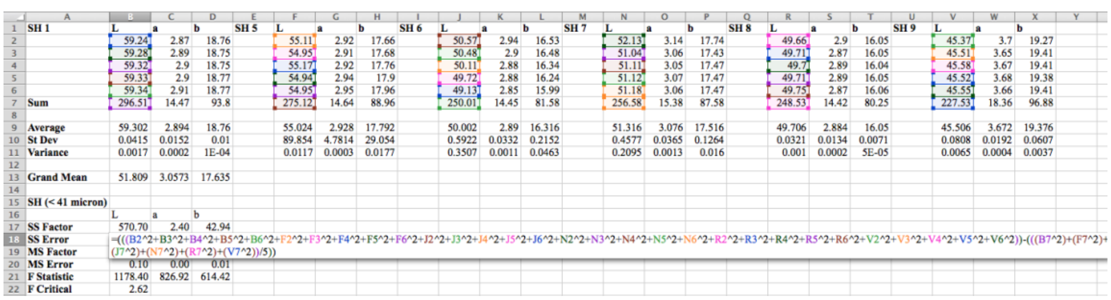
The series of annotated pictures below depict the method for completing ANOVA calculations for soil color measurement comparisons.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	SH 1	L	a	b	SH 5	L	a	b	SH 6	L	a	b	SH 7	L	a	b	SH 8	L	a	b	SH 9	L	a	b
2		59.24	2.87	18.76		55.11	2.92	17.66		50.57	2.94	16.53		52.13	3.14	17.74		49.66	2.9	16.05		45.37	3.7	19.27
3		59.28	2.89	18.75		54.95	2.91	17.68		50.48	2.9	16.48		51.04	3.06	17.43		49.71	2.87	16.05		45.51	3.65	19.41
4		59.32	2.9	18.75		55.17	2.92	17.76		50.11	2.88	16.34		51.11	3.05	17.47		49.7	2.89	16.04		45.58	3.67	19.41
5		59.33	2.9	18.77		54.94	2.94	17.9		49.72	2.88	16.24		51.12	3.07	17.47		49.71	2.89	16.05		45.52	3.68	19.38
6		59.34	2.91	18.77		54.95	2.95	17.96		49.13	2.85	15.99		51.18	3.06	17.47		49.75	2.87	16.06		45.55	3.66	19.41
7	Sum	296.51	14.47	93.8		275.12	14.64	88.96		250.01	14.45	81.58		256.58	15.38	87.58		248.53	14.42	80.25		227.53	18.36	96.88
8																								
9	Average	59.302	2.894	18.76		55.024	2.928	17.792		50.002	2.89	16.316		51.316	3.076	17.516		49.706	2.884	16.05		45.506	3.672	19.376
10	St Dev	0.0415	0.0152	0.01		89.854	4.7814	29.054		0.5922	0.0332	0.2152		0.4577	0.0365	0.1264		0.0321	0.0134	0.0071		0.0808	0.0192	0.0607
11	Variance	0.0017	0.0002	1E-04		0.0117	0.0003	0.0177		0.3507	0.0011	0.0463		0.2095	0.0013	0.016		0.001	0.0002	5E-05		0.0065	0.0004	0.0037
12																								
13	Grand Mean	51.809	3.0573	17.635																				
14																								
15	SH (< 41 micron)																							
16		L	a	b																				
17	SS Factor	=((B7^2/5)+(F7^2/5)+(J7^2/5)+(N7^2/5)+(R7^2/5)+(V7^2/5))-((SUM(B2:B6,F2:F6,J2:J6,N2:N6,R2:R6,V2:V6)^2)/30)																						
18	SS Error	2.32	0.01	0.34																				
19	MS Factor	114.14	0.48	8.59																				
20	MS Error	0.10	0.00	0.01																				
21	F Statistic	1178.40	826.92	614.42																				
22	F Critical	2.62																						

Step 1: All soil color measurements should be entered into a Microsoft Excel spreadsheet similar to the layout above. The sum, average, standard deviation, and variance for each set of soil sample color measurements should be noted as well.

The sum of squares for the factor (SS Factor): square the sum of each set of soil color measurements (above, from each of the six Sherman Circle samples). Subtract from that value the square of the sum of all measurements from all samples taken at that location. That value is then divided by the number of measurements taken (above, 30).



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y
1	SH 1	L	a	b	SH 5	L	a	b	SH 6	L	a	b	SH 7	L	a	b	SH 8	L	a	b	SH 9	L	a	b	
2		59.24	2.87	18.76		55.11	2.92	17.66		50.57	2.94	16.53		52.13	3.14	17.74		49.66	2.9	16.05		45.37	3.7	19.27	
3		59.28	2.89	18.75		54.95	2.91	17.68		50.48	2.9	16.48		51.04	3.06	17.43		49.71	2.87	16.05		45.51	3.65	19.41	
4		59.32	2.9	18.75		55.17	2.92	17.76		50.11	2.88	16.34		51.11	3.05	17.47		49.7	2.89	16.04		45.58	3.67	19.41	
5		59.33	2.9	18.77		54.94	2.94	17.9		49.72	2.88	16.24		51.12	3.07	17.47		49.71	2.89	16.05		45.52	3.68	19.38	
6		59.34	2.91	18.77		54.95	2.95	17.96		49.13	2.85	15.99		51.18	3.06	17.47		49.75	2.87	16.06		45.55	3.66	19.41	
7	Sum	296.51	14.47	93.8		275.12	14.64	88.96		250.01	14.45	81.58		256.58	15.38	87.58		248.53	14.42	80.25		227.53	18.36	96.88	
8																									
9	Average	59.302	2.894	18.76		55.024	2.928	17.792		50.002	2.89	16.316		51.316	3.076	17.516		49.706	2.884	16.05		45.506	3.672	19.376	
10	St Dev	0.0415	0.0152	0.01		89.854	4.7814	29.054		0.5922	0.0332	0.2152		0.4577	0.0365	0.1264		0.0321	0.0134	0.0071		0.0808	0.0192	0.0607	
11	Variance	0.0017	0.0002	1E-04		0.0117	0.0003	0.0177		0.3507	0.0011	0.0463		0.2095	0.0013	0.016		0.001	0.0002	5E-05		0.0065	0.0004	0.0037	
12																									
13	Grand Mean	51.809	3.0573	17.635																					
14																									
15	SH (< 41 micron)																								
16		L	a	b																					
17	SS Factor	570.70	2.40	42.94																					
18	SS Error	=(((B2^2+B3^2+B4^2+B5^2+B6^2+F2^2+F3^2+F4^2+F5^2+F6^2+J2^2+J3^2+J4^2+J5^2+J6^2+N2^2+N3^2+N4^2+N5^2+N6^2+R2^2+R3^2+R4^2+R5^2+R6^2+V2^2+V3^2+V4^2+V5^2+V6^2))-(((B7^2)+(F7^2)+ (J7^2)+(N7^2)+(R7^2)+(V7^2))/5))																							
19	MS Factor																								
20	MS Error	0.10	0.00	0.01																					
21	F Statistic	1178.40	826.92	614.42																					
22	F Critical	2.62																							

Step 2: Calculate the sum of squares for the error (SS Error). Each individual soil color measurement is squared and summed; this value is subtracted by the sum of the squares of each set of measurement's sum (above, square the sum of SH1, SH2, SH3… and sum those values together).

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**SH 1**	**L**	**a**	**b**	**SH 5**	**L**	**a**	**b**	**SH 6**	**L**	**a**	**b**	**SH 7**	**L**	**a**	**b**	**SH 8**	**L**	**a**	**b**	**SH 9**	**L**	**a**	**b**
2		59.24	2.87	18.76		55.11	2.92	17.66		50.57	2.94	16.53		52.13	3.14	17.74		49.66	2.9	16.05		45.37	3.7	19.27
3		59.28	2.89	18.75		54.95	2.91	17.68		50.48	2.9	16.48		51.04	3.06	17.43		49.71	2.87	16.05		45.51	3.65	19.41
4		59.32	2.9	18.75		55.17	2.92	17.76		50.11	2.88	16.34		51.11	3.05	17.47		49.7	2.89	16.04		45.58	3.67	19.41
5		59.33	2.9	18.77		54.94	2.94	17.9		49.72	2.88	16.24		51.12	3.07	17.47		49.71	2.89	16.05		45.52	3.68	19.38
6		59.34	2.91	18.77		54.95	2.95	17.96		49.13	2.85	15.99		51.18	3.06	17.47		49.75	2.87	16.06		45.55	3.66	19.41
7	**Sum**	296.51	14.47	93.8		275.12	14.64	88.96		250.01	14.45	81.58		256.58	15.38	87.58		248.53	14.42	80.25		227.53	18.36	96.88
8																								
9	**Average**	59.302	2.894	18.76		55.024	2.928	17.792		50.002	2.89	16.316		51.316	3.076	17.516		49.706	2.884	16.05		45.506	3.672	19.376
10	**St Dev**	0.0415	0.0152	0.01		89.854	4.7814	29.054		0.5922	0.0332	0.2152		0.4577	0.0365	0.1264		0.0321	0.0134	0.0071		0.0808	0.0192	0.0607
11	**Variance**	0.0017	0.0002	1E-04		0.0117	0.0003	0.0177		0.3507	0.0011	0.0463		0.2095	0.0013	0.016		0.001	0.0002	5E-05		0.0065	0.0004	0.0037
12																								
13	**Grand Mean**	51.809	3.0573	17.635																				
14																								
15	**SH (< 41 micron)**																							
16		L	a	b																				
17	**SS Factor**	570.70	2.40	42.94																				
18	**SS Error**	2.32	0.01	0.34																				
19	**MS Factor**	=B17/5	0.48	8.59																				
20	**MS Error**	0.10	0.00	0.01																				
21	**F Statistic**	1178.40	826.92	614.42																				
22	**F Critical**	2.62																						

Step 3: Calculate the mean square of the factors (MS Factor). To do this, divide the SS Factor by the number of degrees of freedom in your data set. In this case, degrees of freedom = 5 because there are 6 sample sets.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**SH 1**	**L**	**a**	**b**	**SH 5**	**L**	**a**	**b**	**SH 6**	**L**	**a**	**b**	**SH 7**	**L**	**a**	**b**	**SH 8**	**L**	**a**	**b**	**SH 9**	**L**	**a**	**b**
2		59.24	2.87	18.76		55.11	2.92	17.66		50.57	2.94	16.53		52.13	3.14	17.74		49.66	2.9	16.05		45.37	3.7	19.27
3		59.28	2.89	18.75		54.95	2.91	17.68		50.48	2.9	16.48		51.04	3.06	17.43		49.71	2.87	16.05		45.51	3.65	19.41
4		59.32	2.9	18.75		55.17	2.92	17.76		50.11	2.88	16.34		51.11	3.05	17.47		49.7	2.89	16.04		45.58	3.67	19.41
5		59.33	2.9	18.77		54.94	2.94	17.9		49.72	2.88	16.24		51.12	3.07	17.47		49.71	2.89	16.05		45.52	3.68	19.38
6		59.34	2.91	18.77		54.95	2.95	17.96		49.13	2.85	15.99		51.18	3.06	17.47		49.75	2.87	16.06		45.55	3.66	19.41
7	**Sum**	296.51	14.47	93.8		275.12	14.64	88.96		250.01	14.45	81.58		256.58	15.38	87.58		248.53	14.42	80.25		227.53	18.36	96.88
8																								
9	**Average**	59.302	2.894	18.76		55.024	2.928	17.792		50.002	2.89	16.316		51.316	3.076	17.516		49.706	2.884	16.05		45.506	3.672	19.376
10	**St Dev**	0.0415	0.0152	0.01		89.854	4.7814	29.054		0.5922	0.0332	0.2152		0.4577	0.0365	0.1264		0.0321	0.0134	0.0071		0.0808	0.0192	0.0607
11	**Variance**	0.0017	0.0002	1E-04		0.0117	0.0003	0.0177		0.3507	0.0011	0.0463		0.2095	0.0013	0.016		0.001	0.0002	5E-05		0.0065	0.0004	0.0037
12																								
13	**Grand Mean**	51.809	3.0573	17.635																				
14																								
15	**SH (< 41 micron)**																							
16		L	a	b																				
17	**SS Factor**	570.70	2.40	42.94																				
18	**SS Error**	2.32	0.01	0.34																				
19	**MS Factor**	114.14	0.48	8.59																				
20	**MS Error**	=B18/24		0.01																				
21	**F Statistic**	1178.40	826.92	614.42																				
22	**F Critical**	2.62																						

Step 4: Calculate the mean square of the error (MS Error). To do this, divide the SS Error by the number of degrees of freedom in your data set. In this case, degrees of freedom = 24 because there are 30 total measurements and 6 sample sets.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**SH 1**	**L**	**a**	**b**	**SH 5**	**L**	**a**	**b**	**SH 6**	**L**	**a**	**b**	**SH 7**	**L**	**a**	**b**	**SH 8**	**L**	**a**	**b**	**SH 9**	**L**	**a**	**b**
2		59.24	2.87	18.76		55.11	2.92	17.66		50.57	2.94	16.53		52.13	3.14	17.74		49.66	2.9	16.05		45.37	3.7	19.27
3		59.28	2.89	18.75		54.95	2.91	17.68		50.48	2.9	16.48		51.04	3.06	17.43		49.71	2.87	16.05		45.51	3.65	19.41
4		59.32	2.9	18.75		55.17	2.92	17.76		50.11	2.88	16.34		51.11	3.05	17.47		49.7	2.89	16.04		45.58	3.67	19.41
5		59.33	2.9	18.77		54.94	2.94	17.9		49.72	2.88	16.24		51.12	3.07	17.47		49.71	2.89	16.05		45.52	3.68	19.38
6		59.34	2.91	18.77		54.95	2.95	17.96		49.13	2.85	15.99		51.18	3.06	17.47		49.75	2.87	16.06		45.55	3.66	19.41
7	**Sum**	296.51	14.47	93.8		275.12	14.64	88.96		250.01	14.45	81.58		256.58	15.38	87.58		248.53	14.42	80.25		227.53	18.36	96.88
8																								
9	**Average**	59.302	2.894	18.76		55.024	2.928	17.792		50.002	2.89	16.316		51.316	3.076	17.516		49.706	2.884	16.05		45.506	3.672	19.376
10	**St Dev**	0.0415	0.0152	0.01		89.854	4.7814	29.054		0.5922	0.0332	0.2152		0.4577	0.0365	0.1264		0.0321	0.0134	0.0071		0.0808	0.0192	0.0607
11	**Variance**	0.0017	0.0002	1E-04		0.0117	0.0003	0.0177		0.3507	0.0011	0.0463		0.2095	0.0013	0.016		0.001	0.0002	5E-05		0.0065	0.0004	0.0037
12																								
13	**Grand Mean**	51.809	3.0573	17.635																				
14																								
15	**SH (< 41 micron)**																							
16		L	a	b																				
17	**SS Factor**	570.70	2.40	42.94																				
18	**SS Error**	2.32	0.01	0.34																				
19	**MS Factor**	114.14	0.48	8.59																				
20	**MS Error**	0.10	0.00	0.01																				
21	**F Statistic**	=B19/B20		614.42																				
22	**F Critical**	2.62																						

Step 5: Calculate the F Statistic. This is the value which will be used to determine if your data set is or is not statistically different. To do this, divide the MS Factor by the MS Error. The F critical value is a set number that is defined by the number of degrees of freedom in your data set, and can be looked up in statistical textbooks and online resources.

Above, the F statistic is calculated to be 1178, which is larger than the F critical value of 2.62. The soil samples collected from the Sherman Circle location are all statistically different in all L, a, and b values for the <41 micron fraction.

Appendix 6: Raw Soil Color Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	SH 1	L	a	b	SH 5	L	a	b	SH 6	L	a	b	SH 7	L	a	b	SH 8	L	a	b	SH 9	L	a	b
2		38	2.52	13.16		39.17	2.77	13.48		42.11	2.76	14.73		36.71	2.37	12.98		45.49	2.87	15.64		45.87	2.56	15.33
3		39.21	2.69	13.48		41.51	2.71	14		43.16	2.51	13.68		36.83	2.35	12.99		45.57	2.94	15.63		45.74	2.55	15.3
4		42.73	2.7	14.81		40.24	2.71	14.13		43.18	2.45	13.7		39.57	2.52	14.12		43.1	2.96	14.69		36.19	2.46	13.72
5		42.66	2.74	14.75		40.23	2.75	14.13		38.28	2.27	12.43		39.63	2.54	14.14		43.37	2.97	14.76				
6		43.49	2.73	14.91		40.7	3.03	14.21						38.57	2.7	13.25		38.17	2.59	13.42				
7	Sum	206.1	13.38	71.11		201.9	13.97	69.95		166.7	9.990	54.54		191.3	12.48	67.48		215.7	14.33	74.14		127.8	7.570	44.35
8	Average	41.22	2.676	14.222		67.28	2.794	23.32		41.68	2.498	13.64		38.26	2.496	13.50		43.14	2.866	14.83		42.60	2.523	14.78
9	St Dev	2.445	0.090	0.833		65.93	4.564	22.847		2.323	0.203	0.941		1.426	0.143	0.589		3.008	0.159	0.909		5.552	0.055	0.921
10	Variance	4.783	0.006	0.555		3622	17.360	434.99		4.046	0.031	0.664		1.627	0.016	0.277		7.237	0.020	0.662		20.55	0.002	0.565
11																								
12	Grand Mean	45.698	2.642	15.714																				
13																								
14	SH (Bulk Soil Sample)																							
15																								
16		L	a	b																				
17	SS Factor	71.92	0.599	6.847																				
18	SS Error	3717	13.05	423.2																				
19	MS Factor	14.38	0.120	1.369																				
20	MS Error	177.0	0.62	20.15																				
21	F Statistic	0.081	0.193	0.068																				
22	F Critical	2.680																						

Sherman Circle undisturbed soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	SH 5	L	a	b	SH 6	L	a	b	SH 7	L	a	b	SH 8	L	a	b	SH 9	L	a	b
2		57.70	2.930	15.60		57.16	2.840	16.13		55.66	3.310	18.09		54.73	3.300	16.30		42.31	3.580	15.63
3		57.24	3.020	15.80		57.25	2.820	16.10		55.57	3.130	17.81		53.38	3.300	16.39		42.81	3.560	15.89
4		57.06	3.010	15.73		57.45	2.810	16.02		55.59	3.140	17.79		52.95	3.410	16.46		43.11	3.650	16.05
5		57.15	2.960	15.50		57.59	2.770	15.97		55.53	3.120	17.75		53.08	3.400	16.30		43.85	3.760	16.51
6		57.37	2.920	15.47		57.71	2.770	15.93		55.49	3.140	17.70		53.37	3.370	16.17		44.11	3.760	16.60
7	Sum	286.5	14.84	78.10		287.2	14.01	80.15		277.8	15.84	89.14		267.5	16.78	81.62		216.2	18.31	80.68
8	Average	57.30	2.968	15.62		57.43	2.802	16.03		55.57	3.168	17.83		53.50	3.356	16.32		43.24	3.662	16.14
9	St Dev	0.249	0.045	0.143		93.79	4.576	26.18		0.064	0.080	0.152		0.711	0.053	0.109		0.741	0.095	0.412
10	Variance	0.050	0.002	0.016		7330	17.448	571.0		0.003	0.005	0.019		0.405	0.002	0.010		0.439	0.007	0.136
11																				
12	Grand Mean	53.41	3.191	16.39																
13																				
14	SH (> 130 micron)																			
15																				
16		L	a	b																
17	SS Factor	697.4	2.253	14.30																
18	SS Error	4.693	0.085	0.930																
19	MS Factor	139.5	0.451	2.859																
20	MS Error	0.196	0.004	0.039																
21	F Statistic	713.2	126.6	73.78																
22	F Critical	2.620																		

Sherman Circle >130 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	SH 1	L	a	b	SH 5	L	a	b	SH 6	L	a	b	SH 7	L	a	b	SH 8	L	a	b	SH 9	L	a	b
2		53.28	3.170	16.23		44.44	2.960	14.5		48.98	2.760	15.08		50.78	3.040	16.32		30.67	3.810	13.92		47.75	2.75	16.12
3		54.43	3.200	16.38		43.67	3.040	14.54		48.91	2.760	15.11		50.64	3.090	16.32		29.66	3.870	13.76		46.7	2.84	15.9
4		53.85	3.050	15.87		41.65	3.050	14.31		48.88	2.790	15.07		50.7	3.100	16.33		30.53	3.910	13.87		46.62	2.88	15.95
5						41.28	2.970	14.26		48.31	2.730	14.83		50.67	3.060	16.33		30.01	3.930	13.77		46.64	2.86	15.97
6						40.47	3.030	14.18						50.58	3.050	16.32		33.46	4.010	14.5		46.51	2.82	15.66
7	Sum	161.6	9.42	48.48		211.5	15.05	71.79		195.1	11.04	60.09		253.4	15.34	81.62		154.3	19.53	69.82		234.22	14.15	79.6
8																								
9	Average	53.85	3.140	16.16		70.50	5.017	23.93		48.77	2.760	15.02		50.67	3.068	16.32		30.87	3.906	13.96		46.844	2.83	15.92
10	St Dev	0.575	0.079	0.262		69.10	4.915	23.45		0.310	0.024	0.129		0.074	0.026	0.005		1.506	0.074	0.307		0.51111	0.05	0.16688
11	Variance	0.220	0.004	0.046		3978	20.135	458.132		0.072	0.000	0.013		0.004	0.001	0.000		1.813	0.004	0.075		0.20898	0.002	0.02228
12																								
13	Grand Mean	50.25	3.453	16.89																				
14																								
15	SH (130-60 micron)																							
16		L	a	b																				
17	SS Factor	1504	4.100	22.95																				
18	SS Error	5405	17.98	494.7																				
19	MS Factor	300.9	0.820	4.589																				
20	MS Error	257.4	0.856	23.56																				
21	F Statistic	1.169	0.958	0.195																				
22	F Critical	2.680																						

Sherman Circle 130-60 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**SH 1**	**L**	**a**	**b**	**SH 5**	**L**	**a**	**b**	**SH 6**	**L**	**a**	**b**	**SH 7**	**L**	**a**	**b**	**SH 8**	**L**	**a**	**b**	**SH 9**	**L**	**a**	**b**
2		50.95	2.88	15.36		48.43	2.770	14.48		45.83	2.910	14.55		52.72	3.010	16.91		36.13	3.640	14.55		47.98	2.950	16.30
3		52.21	2.81	15.59		48.46	2.770	14.48		45.59	2.900	14.57		52.58	3.010	16.89		35.85	3.600	14.63		47.33	2.940	16.20
4		52.33	2.85	15.61		48.33	2.780	14.51		45.59	2.870	14.59		52.49	2.980	16.85		35.93	3.610	14.63		47.63	2.990	16.33
5						48.24	2.780	14.51		45.59	2.860	14.59		52.48	2.960	16.84		35.48	3.590	14.56		47.60	3.010	16.32
6						48.27	2.800	14.54		45.56	2.880	14.62		52.43	2.990	16.82		35.39	3.620	14.56		47.60	3.000	16.32
7	Sum	155.5	8.54	46.56		241.7	13.90	72.52		228.2	14.42	72.92		262.7	14.95	84.31		178.8	18.06	72.93		238.1	14.89	81.47
8																								
9	Average	51.83	2.847	15.52		48.35	2.78	14.504		45.63	2.884	14.58		52.54	2.99	16.86		35.76	3.612	14.59		47.63	2.978	16.29
10	St Dev	0.764	0.035	0.139		78.95	4.540	23.685		0.111	0.021	0.026		0.114	0.021	0.037		0.312	0.019	0.040		0.231	0.031	0.054
11	Variance	0.390	0.001	0.013		5194	17.17	467.5		0.010	0.000	0.001		0.010	0.000	0.001		0.078	0.000	0.001		0.043	0.001	0.002
12																								
13	Grand Mean	46.96	3.015	15.39																				
14																								
15	SH (60-41 micron)																							
16		L	a	b																				
17	SS Factor	871.6	2.235	25.37																				
18	SS Error	3226	9.736	289.1																				
19	MS Factor	174.3	0.447	5.075																				
20	MS Error	146.6	0.443	13.14																				
21	F Statistic	1.189	1.010	0.386																				
22	F Critical	2.660																						

Sherman Circle 60-41 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**SH 1**	**L**	**a**	**b**	**SH 5**	**L**	**a**	**b**	**SH 6**	**L**	**a**	**b**	**SH 7**	**L**	**a**	**b**	**SH 8**	**L**	**a**	**b**	**SH 9**	**L**	**a**	**b**
2		59.24	2.870	18.76		55.11	2.920	17.66		50.57	2.940	16.53		52.13	3.140	17.74		49.66	2.900	16.05		45.37	3.700	19.27
3		59.28	2.890	18.75		54.95	2.910	17.68		50.48	2.900	16.48		51.04	3.060	17.43		49.71	2.870	16.05		45.51	3.650	19.41
4		59.32	2.900	18.75		55.17	2.920	17.76		50.11	2.880	16.34		51.11	3.050	17.47		49.70	2.890	16.04		45.58	3.670	19.41
5		59.33	2.900	18.77		54.94	2.940	17.9		49.72	2.880	16.24		51.12	3.070	17.47		49.71	2.890	16.05		45.52	3.680	19.38
6		59.34	2.910	18.77		54.95	2.950	17.96		49.13	2.850	15.99		51.18	3.060	17.47		49.75	2.870	16.06		45.55	3.660	19.41
7	Sum	296.5	14.47	93.80		275.1	14.64	88.96		250.0	14.45	81.58		256.6	15.38	87.58		248.5	14.42	80.25		227.5	18.36	96.88
8																								
9	Average	59.30	2.894	18.76		55.02	2.928	17.79		50.00	2.890	16.32		51.32	3.076	17.52		49.71	2.884	16.05		45.51	3.672	19.38
10	St Dev	0.041	0.015	0.010		89.85	4.781	29.05		0.592	0.033	0.215		0.458	0.036	0.126		0.032	0.013	0.007		0.081	0.019	0.061
11	Variance	0.002	0.000	0.000		0.012	0.000	0.018		0.351	0.001	0.046		0.210	0.001	0.016		0.001	0.000	0.000		0.007	0.000	0.004
12																								
13	Grand Mean	51.81	3.057	17.64																				
14																								
15	SH (< 41 micron)																							
16		L	a	b																				
17	SS Factor	570.7	2.398	42.938																				
18	SS Error	2.325	0.014	0.335																				
19	MS Factor	114.1	0.480	8.588																				
20	MS Error	0.097	0.001	0.014																				
21	F Statistic	1178	826.9	614.4																				
22	F Critical	2.620																						

Sherman Circle < 41 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	**RC 1**	**L**	**a**	**b**	**RC 2**	**L**	**a**	**b**	**RC 3**	**L**	**a**	**b**	**RC 4**	**L**	**a**	**b**	**RC 5**	**L**	**a**	**b**	**RC 6**	**L**	**a**	**b**
2		45.14	1.660	12.19		36.26	1.370	9.840		43.33	0.230	8.440		44.75	1.400	11.97		41.04	2.220	12.52		43.43	1.740	13.24
3		44.69	1.920	12.80		36.51	1.340	9.700		43.70	0.470	8.940		45.91	1.690	12.44		41.00	2.220	12.52		42.78	1.850	13.47
4		44.06	1.870	12.66		36.50	1.270	9.710		44.28	0.690	9.370		46.55	1.690	12.69		40.98	2.220	12.41		43.03	1.860	13.43
5		42.55	1.770	12.34		36.56	1.270	9.710		44.14	0.890	9.650		46.99	1.710	12.62		40.78	2.220	12.45		41.05	1.740	12.57
6		42.37	1.750	12.23		36.55	1.290	9.790		44.22	0.900	9.740		45.28	1.790	12.66		40.69	2.200	12.44		41.37	1.660	12.07
7		42.53	1.710	12.22		36.37	1.370	9.890		44.15	0.910	9.770		45.24	1.810	12.89		40.69	2.200	12.37		41.33	1.660	12.04
8		42.55	1.700	12.22		36.58	1.350	9.800		44.03	0.900	9.750		45.30	1.790	12.80		41.10	2.210	12.41		41.14	1.590	11.82
9		42.56	1.760	12.21		36.45	1.370	9.830		43.92	0.960	9.890		45.42	1.790	12.79		41.37	2.160	12.48		41.48	1.590	11.96
10		43.10	1.690	12.18		36.30	1.360	9.910		44.03	0.960	9.820		45.19	1.760	12.59		41.13	2.190	12.48		41.42	1.540	11.80
11		43.51	1.670	12.24		36.24	1.400	9.930		43.79	0.960	9.870		44.67	1.730	12.60		41.10	2.200	12.46		41.78	1.570	11.96
12	Sum	433.1	17.50	123.3		364.3	13.39	98.11		439.6	7.870	95.24		455.3	17.16	126.1		409.9	22.04	124.5		418.8	16.80	124.4
13	Average	43.31	1.750	12.33		36.43	1.339	9.811		43.96	0.787	9.524		45.53	1.716	12.61		40.99	2.204	12.45		41.88	1.680	12.44
14	St Dev	1.006	0.086	0.218		0.130	0.046	0.085		0.287	0.250	0.478		0.745	0.120	0.257		0.215	0.019	0.049		0.864	0.114	0.687
15	Variance	0.911	0.007	0.043		0.015	0.002	0.006		0.074	0.056	0.206		0.499	0.013	0.059		0.041	0.000	0.002		0.672	0.012	0.425
16		L	a	b																				
17	SS Factor	500.4	11.34	104.5																				
18	SS Error	22.13	0.895	7.414																				
19	MS Factor	100.1	2.267	20.90																				
20	MS Error	0.410	0.017	0.137																				
21	F Statistic	244.3	136.7	152.2																				
22	F Critical	2.390																						

Rock Creek Park undisturbed soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	RC 1	L	a	b	RC2	L	a	b	RC3	L	a	b	RC4	L	a	b	RC5	L	a	b	RC6	L	a	b
2		48.79	1.270	12.4		47.84	1.450	12.22		48.99	1.200	12.39		44.67	1.590	12.17		45.76	1.620	12.35		45.81	0.670	13.39
3		48.85	0.750	11.04		47.81	1.360	12.29		49.49	1.200	12.61		45.95	1.430	12.18		45.30	1.680	12.44		45.83	0.660	13.44
4		45.37	0.590	10.69		47.73	1.520	12.81		49.53	1.240	12.73		46.54	1.420	12.30		45.42	1.660	12.42		45.67	0.660	13.49
5		46.16	0.600	10.8		47.71	1.510	12.94		49.63	1.270	12.70		46.77	1.420	12.36		45.41	1.680	12.44		45.77	0.680	13.58
6		46.12	0.600	10.64		47.7	1.500	12.86		49.80	1.170	12.68		46.87	1.460	12.38		45.38	1.670	12.47		46.00	0.660	13.60
7		46.11	0.650	10.66		47.72	1.500	12.83		49.72	1.230	12.69		46.97	11.43	12.44		45.37	1.680	12.44		46.01	0.690	13.62
8		46.33	0.630	10.67		47.66	1.420	12.83		49.80	1.240	12.71		46.98	1.440	12.44		45.41	1.710	12.44		45.90	0.700	13.63
9		47.56	1.300	12.06		47.43	1.370	12.71		50.01	1.180	12.85		46.94	1.440	12.45		45.41	1.700	12.43		45.91	0.720	13.65
10		47.35	1.370	12.09		47.12	1.360	12.69		50.07	1.190	12.53		46.92	1.440	12.45		45.66	1.670	12.40		45.90	0.700	13.62
11		47.32	1.300	12.03		47.24	1.510	12.62		50.01	1.340	13.09		46.95	1.440	12.45		45.76	1.650	12.41		45.88	0.730	13.58
12	Sum	470.0	9.060	113.1		476.0	14.50	126.8		497.1	12.26	127.0		465.6	24.51	123.6		454.9	16.72	124.2		458.7	6.870	135.6
13	Average	47.00	0.906	11.31		47.60	1.450	12.68		49.71	1.226	12.698		46.56	2.451	12.36		45.49	1.672	12.42		45.87	0.687	13.56
14	St Dev	1.181	0.351	0.736		0.247	0.067	0.243		134.9	3.327	34.458		0.734	3.155	0.110		0.170	0.025	0.032		0.103	0.025	0.089
15	Variance	1.254	0.111	0.488		0.055	0.004	0.053		0.093	0.002	0.031		0.486	8.960	0.011		0.026	0.001	0.001		0.010	0.001	0.007
16		L	a	b																				
17	SS Factor	114.3	19.64	26.41																				
18	SS Error	131544	214.0	9322																				
19	MS Factor	22.86	3.928	5.281																				
20	MS Error	2436	3.963	172.6																				
21	F Statistic	0.009	0.991	0.031																				
22	F Critical	2.390																						

Rock Creek Park >130 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	RC 1	L	a	b	RC 2	L	a	b	RC 3	L	a	b	RC4	L	a	b	RC5	L	a	b	RC6	L	a	b
2		50.53	1.340	13.56		49.79	1.420	14.01		50.50	1.450	15.32		45.49	1.640	12.36		44.95	1.850	12.46		46.53	1.970	13.13
3		50.43	1.400	13.56		49.77	1.410	14.02		50.41	1.480	15.32		45.45	1.660	12.34		44.98	1.830	12.47		46.55	1.990	13.11
4		50.39	1.380	13.58		49.73	1.410	14.02		50.28	1.510	15.34		45.32	1.710	12.29		44.98	1.810	12.53		46.55	1.990	13.12
5		50.36	1.360	13.60		49.71	1.430	14.02		50.22	1.450	15.40		45.19	1.680	12.23		44.99	1.820	12.52		46.56	2.000	13.10
6		50.35	1.360	13.60		49.70	1.420	14.01		50.19	1.470	15.39		45.14	1.720	12.22		44.98	1.830	12.51		46.73	1.970	13.09
7		49.82	1.460	13.66		49.69	1.420	14.03		50.20	1.460	15.40		46.12	1.670	12.14		44.99	1.810	12.51		46.77	1.970	13.08
8		50.18	1.420	13.59		49.71	1.440	14.04		50.34	1.440	15.43		46.54	1.670	12.23		44.99	1.830	12.52		46.81	1.970	13.08
9		49.88	1.420	13.64		49.93	1.450	13.67		50.57	1.440	15.36		46.73	1.660	12.25		44.99	1.830	12.53		46.81	1.990	13.08
10		49.86	1.420	13.64		49.93	1.450	13.89		50.58	1.380	15.39		46.95	1.630	12.31		45.00	1.820	12.52		46.88	2.000	13.09
11		49.86	1.450	13.66		49.94	1.450	13.64		50.20	1.380	15.35		47.12	1.640	12.34		44.99	1.860	12.51		46.99	1.950	13.13
12	Sum	501.7	14.01	136.1		497.9	14.30	139.4		503.5	14.46	153.7		460.1	16.68	122.7		449.8	18.29	125.1		467.2	19.80	131.0
13	Average	50.17	1.401	13.61		49.79	1.430	13.94		50.35	1.446	15.37		46.01	1.668	12.27		44.98	1.829	12.51		46.72	1.980	13.10
14	St Dev	0.2814	0.0401	0.0384		0.1036	0.0163	0.1536		0.1563	0.0406	0.0374		0.7758	0.0294	0.0690		0.0135	0.0160	0.0239		0.1622	0.0163	0.0202
15	Variance	0.0713	0.0014	0.0013		0.0097	0.0002	0.0212		0.0220	0.0015	0.0013		0.5416	0.0008	0.0043		0.0002	0.0002	0.0005		0.0237	0.0002	0.0004
16		L	a	b																				
17	SS Factor	281.3	2.897	63.45																				
18	SS Error	137159	159.9	10834																				
19	MS Factor	56.27	0.579	12.69																				
20	MS Error	2540	2.961	200.6																				
21	F Statistic	0.022	0.196	0.063																				
22	F Critical	2.390																						

Rock Creek Park 130-60 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	RC 1	L	a	b	RC 2	L	a	b	RC 3	L	a	b	RC 4	L	a	b	RC 5	L	a	b	RC6	L	a	b
2		50.87	1.480	13.81		46.18	1.750	12.84		50.27	1.720	15.77		41.87	2.010	11.65		43.07	2.090	12.34		45.16	2.220	14.57
3		50.87	1.490	13.82		46.03	1.750	12.81		50.19	1.740	15.75		41.82	1.980	11.6		43.02	2.130	12.32		44.51	2.280	14.43
4		50.84	1.500	13.81		45.69	1.780	12.72		50.02	1.780	15.82		41.89	2.030	11.64		43.01	2.160	12.30		44.37	2.280	14.17
5		50.84	1.520	13.79		45.59	1.790	12.69		50.02	1.790	15.82		41.77	2.010	11.59		43.01	2.110	12.32		44.23	2.260	14.06
6		50.84	1.520	13.79		45.43	1.790	12.64		49.48	1.750	15.85		41.64	1.990	11.56		43.02	2.140	12.31		44.12	2.260	13.99
7		50.71	1.510	13.77		45.73	1.790	12.67		49.32	1.740	15.90		41.72	2.030	11.57		43.01	2.160	12.30		44.11	2.300	13.94
8		50.67	1.500	13.78		45.77	1.810	12.68		49.37	1.740	15.88		41.70	2.010	11.56		43.02	2.130	12.31		44.03	2.300	13.85
9		50.93	1.510	13.81		46.07	1.790	12.72		49.36	1.710	15.91		41.70	2.040	11.56		42.99	2.110	12.33		43.95	2.280	13.80
10		51.10	1.500	13.83		46.06	1.800	12.72		49.31	1.780	15.90		41.69	2.020	11.57		42.97	2.130	12.31		43.96	2.270	13.80
11		51.10	1.490	13.82										41.68	2.040	11.56		43.02	2.130	12.32		43.94	2.300	13.77
12	Sum	508.8	15.02	138.0		412.6	16.05	114.5		447.3	15.75	142.6		417.5	20.16	115.9		430.1	21.29	123.2		442.4	22.75	140.4
13	Average	50.88	1.502	13.80		45.84	1.783	12.72		49.70	1.750	15.84		41.75	2.016	11.59		43.01	2.129	12.32		44.24	2.275	14.04
14	St Dev	0.1403	0.0132	0.0195		0.2557	0.0206	0.0651		0.4091	0.0278	0.0585		0.0855	0.0201	0.0341		0.0255	0.0218	0.0126		0.3748	0.0246	0.2763
15	Variance	0.0177	0.0002	0.0003		0.0581	0.0004	0.0038		0.1488	0.0007	0.0030		0.0066	0.0004	0.0010		0.0006	0.0004	0.0001		0.1264	0.0005	0.0687
16		L	a	b																				
17	SS Factor	661.1	3.963	108.2																				
18	SS Error	121272	214.2	10343																				
19	MS Factor	132.2	0.793	21.63																				
20	MS Error	2332	4.120	198.9																				
21	F Statistic	0.057	0.192	0.109																				
22	F Critical	2.390																						

Rock Creek Park 60-41 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	RC 1	L	a	b	RC 2	L	a	b	RC 3	L	a	b	RC 4	L	a	b	RC 5	L	a	b	RC 6	L	a	b
2		51.16	2.060	12.83		51.23	2.050	12.76		55.95	1.910	15.93		51.43	1.920	12.47		48.62	2.160	12.32		53.29	2.300	15.32
3		51.18	2.080	12.87		51.14	2.050	12.75		56.15	1.920	15.98		51.69	1.880	12.53		48.62	2.190	12.32		53.35	2.290	15.34
4		51.17	2.080	12.87		51.16	2.060	12.74		56.15	1.910	15.97		51.70	1.920	12.51		48.62	2.190	12.32		53.35	2.280	15.33
5		51.13	2.090	12.86		51.17	2.040	12.76		56.15	1.940	15.97		51.72	1.900	12.53		48.62	2.190	12.32		53.34	2.290	15.33
6		51.19	2.060	12.87		51.16	2.050	12.75		56.17	1.930	15.98		51.74	1.900	12.52		48.57	2.200	12.32		53.34	2.290	15.32
7		51.21	2.090	12.87		51.16	2.060	12.74		56.23	1.950	15.97		51.75	1.910	12.53		48.57	2.200	12.32		53.36	2.310	15.33
8		51.22	2.090	12.85		51.17	2.080	12.74		56.23	1.930	15.98		51.75	1.900	12.53		48.56	2.210	12.32		53.38	2.250	15.30
9		51.21	2.100	12.85		51.18	2.070	12.74		56.24	1.940	15.99		51.75	1.900	12.53		48.56	2.220	12.31		53.40	2.270	15.30
10		51.23	2.070	12.85		51.19	2.050	12.75		56.25	1.930	15.99		51.75	1.900	12.53		48.57	2.190	12.32		53.41	2.280	15.30
11		51.23	2.090	12.86		51.28	2.080	12.76		56.27	1.950	15.99		51.75	1.920	12.52		48.56	2.200	12.32		53.41	2.270	15.30
12	Sum	511.9	20.81	128.6		511.8	20.59	127.5		561.8	19.31	159.8		517.0	19.05	125.2		485.9	21.95	123.2		533.6	22.83	153.2
13	Average	51.19	2.081	12.86		51.18	2.059	12.75		56.18	1.931	15.98		51.70	1.905	12.52		48.59	2.195	12.32		53.36	2.283	15.32
14	St Dev	0.0330	0.0137	0.0132		0.0414	0.0137	0.0088		0.0927	0.0145	0.0178		0.0986	0.0127	0.0189		0.0287	0.0158	0.0032		0.0377	0.0170	0.0157
15	Variance	0.0010	0.0002	0.0002		0.0015	0.0002	0.0001		0.0077	0.0002	0.0003		0.0087	0.0001	0.0003		0.0007	0.0002	0.0000		0.0013	0.0003	0.0002
16		L	a	b																				
17	SS Factor	323.7	1.08	126.7																				
18	SS Error	161153	257.0	11149																				
19	MS Factor	64.74	0.215	25.34																				
20	MS Error	2984	4.759	206.5																				
21	F Statistic	0.022	0.045	0.123																				
22	F Critical	2.390																						

Rock Creek Park <41 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	MG 1	L	a	b	MG 2	L	a	b	MG 3	L	a	b	MG 4	L	a	b	MG 5	L	a	b	MG 6	L	a	b
2		49.42	3.490	16.56		46.2	3.500	15.54		42.33	3.510	14.25		40.91	3.040	14.65		46.48	3.590	16.95		49.45	4.230	17.79
3		45.11	3.470	15.75		46.05	3.510	15.5		42.37	3.560	14.26		40.47	3.060	14.48		46.51	3.580	16.99		49.38	4.070	17.6
4		43.63	3.580	15.82		45.89	3.550	15.41		42.32	3.570	14.27		40.79	3.050	14.62		46.53	3.560	17.01		49.34	4.010	17.63
5		43.99	3.520	15.88		45.06	3.530	14.99		41.46	3.490	14.41		39.68	3.220	14.27		46.86	3.910	17.71		45.94	3.650	15.96
6		44.36	3.590	15.91		45.06	3.510	15.02		41.45	3.510	14.46		40.25	3.260	14.45		46.83	3.920	17.72		45.74	3.670	15.95
7		44.45	3.590	15.93		45.19	3.510	15.04		41.48	3.510	14.47		40.30	3.280	14.51		46.71	3.950	17.79		45.58	3.700	15.99
8		46.92	3.620	16.30		45.25	3.540	15.12		39.97	3.530	13.77		40.11	3.260	14.43		46.69	3.940	17.81		45.58	3.690	16.04
9		47.03	3.610	16.30		45.36	3.580	15.41		39.71	3.540	13.75		40.71	3.370	14.85		48.51	4.100	18.29		48.63	4.030	17.48
10		47.43	3.630	16.30		45.01	3.640	15.46		44.04	3.760	15.35		41.18	3.350	15.02		48.53	4.070	18.25		48.84	4.040	17.51
11		47.47	3.630	16.32		44.85	3.600	15.56		43.98	3.770	15.34		41.29	3.420	15.04		48.54	4.050	18.21		48.88	4.070	17.50
12	Average	45.98	3.573	16.11		45.39	3.547	15.31		41.91	3.575	14.43		40.57	3.231	14.63		47.22	3.867	17.67		47.74	3.916	16.95
13	Sum	459.8	35.73	161.1		453.9	35.47	153.1		419.1	35.75	144.3		405.7	32.31	146.3		472.2	38.67	176.7		477.4	39.16	169.5
14	Grand Mean	44.80																						
15																								
16		L	a	b																				
17	SS Factor	424.6	3.095	83.77																				
18	SS Error	119737	781.8	15017																				
19	MS Factor	84.93	0.619	16.75																				
20	MS Error	2217.36	14.48	278.09																				
21	F Statistic	0.038	0.043	0.060																				
22	F Critical	2.390																						

Marvin Gaye Park undisturbed soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	MG 1	L	a	b	MG 2	L	a	b	MG 3	L	a	b	MG 4	L	a	b	MG 5	L	a	b	MG 6	L	a	b
2		49.38	4.160	18.11		47.72	3.980	16.94		43.21	3.720	14.65		35.58	3.090	12.29		48.67	3.630	17.2		52.74	2.970	17.55
3		49.59	4.200	18.18		47.78	4.060	17.02		43.2	3.790	14.66		35.82	3.060	12.33		48.64	3.660	17.2		53.25	2.970	17.83
4		49.85	4.260	18.41		47.87	4.100	17.12		43.23	3.800	14.66		35.85	3.060	12.33		48.54	3.650	17.12		53.42	2.980	17.96
5		52.45	4.420	19.09		50.71	4.110	18.01		51.75	3.670	16.91		33.99	3.630	12.72		47.99	3.750	16.8		54.57	2.700	17.95
6		49.49	3.780	16.23		51.01	4.120	18.11		51.74	3.670	16.9		33.95	3.580	12.74		47.95	3.740	16.78		54.78	2.820	18.13
7		50.17	3.750	16.42		46.84	3.890	16.84		43.13	4.180	14.61		38.16	3.200	13.04		47.96	3.690	16.78		54.92	2.870	18.21
8		50.29	3.780	16.62		47.32	3.940	17.00		43.13	4.190	14.6		38.4	3.230	13.06		47.72	3.480	15.93		54.85	2.700	17.72
9		50.28	3.740	16.18		49.79	4.120	17.49		44.3	3.640	14.26		38.65	3.220	13.13		47.71	3.470	15.96		55.53	2.700	17.84
10		50.46	3.790	16.22		49.92	4.170	17.56		44.2	3.630	14.31		40.19	2.990	12.54		47.67	3.460	15.89		55.41	2.750	18.00
11		49.95	3.900	16.34		51.17	3.880	17.86		51.58	3.280	16.73		40.14	3.020	12.51		49.42	3.500	16.73		55.50	2.480	16.83
12	Average	50.19	3.978	17.18		49.01	4.037	17.40		45.947	3.757	15.229		37.073	3.208	12.669		48.227	3.603	16.639		54.497	2.794	17.802
13	Sum	501.9	39.78	171.8		490.1	40.37	174.0		459.47	37.57	152.29		370.73	32.08	126.69		482.27	36.03	166.39		544.97	27.94	178.02
14	Grand Mean	47.49																						
15																								
16		L	a	b																				
17	SS Factor	1702	11.54	185.4																				
18	SS Error	135893	767.6	15711																				
19	MS Factor	425.38	2.88	46.36																				
20	MS Error	3088.48	17.44	357.1																				
21	F Statistic	0.138	0.165	0.130																				
22	F Critical	2.390																						

Marvin Gaye Park >130 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	MG 1	L	a	b	MG 2	L	a	b	MG 3	L	a	b	MG 4	L	a	b	MG 5	L	a	b	MG 6	L	a	b
2		42.84	4.230	16.21		42.46	4.060	16.06		43.68	3.530	14.48		36.76	3.610	13.89		47.04	3.960	18.35		41.14	3.100	14.46
3		42.66	4.280	16.15		42.28	4.060	16.01		43.56	3.550	14.46		36.75	3.610	13.9		46.40	3.980	18.17		40.58	3.110	14.33
4		42.5	4.300	16.08		42.10	4.080	15.91		43.33	3.580	14.43		36.77	3.610	13.89		46.24	3.970	18.13		40.55	3.110	14.33
5		42.49	4.270	16.10		46.46	3.990	16.23		43.32	3.610	14.44		34.89	3.700	13.68		49.26	3.730	17.85		40.40	3.130	14.30
6		42.74	4.220	16.04		46.40	4.020	16.22		46.66	3.370	14.46		37.20	3.530	13.8		49.11	3.750	17.84		40.06	3.140	14.42
7		42.73	4.200	16.05		46.24	4.020	16.22		46.72	3.370	14.49		37.18	3.560	13.8		49.15	3.780	17.86		41.99	2.990	14.45
8		42.75	4.200	16.03		47.75	4.490	17.93		46.73	3.370	14.48		37.15	3.550	13.8		49.58	3.800	17.95		41.92	3.000	14.46
9		42.49	4.220	15.94		47.76	4.470	17.94		41.70	3.740	14.86		37.15	3.590	13.8		49.41	3.830	18.01		41.87	3.010	14.46
10		42.39	4.230	15.94		45.94	4.260	17.19		44.12	3.540	14.23		37.15	3.550	13.8		49.07	3.880	18.12		40.78	3.140	14.87
11		42.34	4.230	15.93		45.95	4.260	17.18		44.13	3.560	14.24		39.14	3.700	13.74		48.10	3.910	18.27		40.79	3.140	14.88
12	Average	42.59	4.238	16.05		45.33	4.171	16.69		44.40	3.522	14.46		37.01	3.601	13.81		48.34	3.859	18.06		41.01	3.087	14.50
13	Sum	425.9	42.38	160.5		453.3	41.71	166.9		444.0	35.22	144.6		370.1	36.01	138.1		483.4	38.59	180.55		410.1	30.87	145.0
14	Grand Mean	43.11																						
15																								
16		L	a	b																				
17	SS Factor	757.6	9.409	131.4																				
18	SS Error	111260	843.6	14578																				
19	MS Factor	189.4	2.352	32.85																				
20	MS Error	2529	19.17	331.3																				
21	F Statistic	0.075	0.123	0.099																				
22	F Critical	2.390																						

Marvin Gaye Park 130-60 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	MG 1	L	a	b	MG 2	L	a	b	MG 3	L	a	b	MG 4	L	a	b	MG 5	L	a	b	MG 6
2		47.64	4.550	17.27		45.32	4.310	17.25		42.85	3.740	14.91		39.58	3.740	14.63		49.55	4.120	19.59	n/a
3		47.86	4.600	17.41		45.21	4.270	17.26		42.75	3.770	14.89		39.61	3.730	14.66		49.57	4.120	19.61	
4		48.97	4.130	17.08		45.21	4.270	17.26		42.76	3.780	14.90		39.63	3.770	14.65		49.57	4.100	19.60	
5		48.93	4.120	17.07		46.93	4.280	17.79		42.73	3.810	14.90		37.18	3.660	14.13		49.56	4.120	19.59	
6		48.97	4.130	17.10		46.93	4.290	17.79		42.72	3.780	14.92		37.17	3.680	14.12		49.06	3.860	18.53	
7		48.97	4.110	17.11		46.93	4.320	17.78		42.72	3.800	14.91		37.09	3.690	14.10		49.02	3.870	18.50	
8		50.93	3.980	16.89		46.94	4.280	17.80		42.73	3.770	14.93		39.17	3.850	14.50		49.02	3.870	18.53	
9		50.71	3.970	16.35		49.04	4.120	17.69		42.75	3.770	14.92		39.85	3.840	14.53		50.04	4.100	19.57	
10		50.68	3.930	16.32		49.03	4.130	17.71		44.51	3.810	15.18		40.04	3.850	14.57		50.03	4.070	19.59	
11		50.67	3.930	16.32		49.26	4.100	17.66		44.58	3.820	15.17		40.11	3.880	14.61		50.04	4.090	19.58	
12	Average	49.43	4.145	16.892		47.08	4.237	17.60		43.11	3.785	14.96		38.94	3.769	14.45		49.55	4.032	19.27	
13	Sum	494.3	41.45	168.92		470.8	42.37	176.0		431.1	37.85	149.6		389.4	37.69	144.5		495.5	40.32	192.7	
14	Grand Mean	38.02																			
15																					
16		L	a	b																	
17	SS Factor	829.7	1.776	155.0																	
18	SS Error	103908	792.0	13856																	
19	MS Factor	207.4	0.444	38.76																	
20	MS Error	2362	18.00	314.9																	
21	F Statistic	0.088	0.025	0.123																	
22	F Critical	2.390																			

Marvin Gaye Park 60-41 micron soil sample color measurements and ANOVA calculations.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
1	MG 1	L	a	b	MG 2	L	a	b	MG 3	L	a	b	MG 4	L	a	b	MG 5	L	a	b	MG 6	L	a	b
2		52.26	4.170	19.32		52.49	4.110	19.09		46.36	3.590	16.26		47.09	3.800	18.89		48.94	3.660	19.31		49.01	3.190	17.82
3		51.91	4.140	19.26		49.45	4.470	20.03		46.22	3.560	16.22		47.31	3.840	18.96		49.08	3.650	19.35		48.79	3.170	17.79
4		51.91	4.150	19.24		49.44	4.490	20.04		46.01	3.570	16.16		47.42	3.830	19.00		49.11	3.630	19.37		48.95	3.180	17.83
5		51.91	4.160	19.24		49.43	4.480	20.03		46.05	3.540	16.20		47.52	3.820	19.02		49.12	3.670	19.36		49.12	3.190	17.87
6		51.91	4.170	19.24		49.43	4.510	20.01		46.04	3.560	16.18		47.58	3.860	19.05		49.14	3.660	19.37		49.09	3.170	17.90
7		51.91	4.150	19.24		49.44	4.510	20.02		45.99	3.580	16.17		47.68	3.860	19.06		49.15	3.650	19.38		49.31	3.190	17.96
8		51.93	4.170	19.25		49.47	4.500	20.02		46.00	3.570	16.16		47.76	3.880	19.07		49.14	3.640	19.37		49.40	3.200	17.98
9		51.93	4.150	19.24		49.48	4.490	20.04		46.01	3.580	16.16		47.95	3.890	19.13		49.17	3.660	19.37		49.50	3.180	18.00
10		51.94	4.140	19.25		49.47	4.480	20.04		46.01	3.600	16.15		48.13	3.870	19.21		49.20	3.630	19.39		49.51	3.180	18.00
11		51.93	4.160	19.23		49.49	4.480	20.02		46.01	3.590	16.15		48.15	3.880	19.21		49.23	3.650	19.39		49.52	3.180	18.02
12	Average	51.95	4.156	19.25		49.76	4.452	19.93		46.07	3.574	16.18		47.66	3.853	19.06		49.13	3.650	19.37		49.22	3.183	17.92
13	Sum	519.5	41.56	192.5		497.6	44.52	199.3		460.7	35.74	161.8		476.6	38.53	190.6		491.3	36.50	193.7		492.2	31.83	179.2
14	Grand Mean	48.97																						
15																								
16		L	a	b																				
17	SS Factor	197.4	10.08	93.18																				
18	SS Error	142621	873.0	20683																				
19	MS Factor	49.36	2.520	23.29																				
20	MS Error	3241	19.84	470.1																				
21	F Statistic	0.015	0.127	0.050																				
22	F Critical	2.390																						

Marvin Gaye Park < 41micron soil sample color measurements and ANOVA calculations.

Appendix 7: Particle Size Distribution Statistical Analysis

Below are the particle size distribution statistical analysis calculations for undisturbed and transferred soil for each of the three locations. The calculations are based off of equations 2-8 in Chapter 6 of this document. The standard deviations used in the equations for the empty and full beakers were 0.0047 and 0.000088, respectively. All sample weights and absolute errors are in grams and all size fractions are in microns.

RCP = Rock Creek Park
SHC = Sherman Circle
MGP = Marvin Gaye Park
R.E. = Relative Error

Rock Creek Park

	Bulk Soil Sample Average Total	Bulk Soil >130	Bulk Soil 130-60	Bulk Soil 60-41	Bulk Soil < 41
	77.16	67.83	4.75	0.58	4
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.8791	0.0616	0.0075	0.0518
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0000	0.0000	0.0000	0.0002	0.0000
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0011	0.0011
Absolute Error	0.0825	0.0725	0.0051	0.0006	0.0043

Transferred Soil Weights	RCP 1 NW Total	RCP 1 NW >130	RCP 1 NW 130-60	RCP 1 NW 60-41	RCP 1 NW <41
	14.2485	14.1564	0.0251	0.0105	0.0001
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9935	0.0018	0.0007	0.0000
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0000	0.0000	0.0035	0.0083	0.8756
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0036	0.0084	0.8756
Absolute Error	0.0152	0.0151	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 1 NJ Total	RCP 1 NJ >130	RCP 1 NJ 130-60	RCP 1 NJ 60-41	RCP 1 NJ < 41
	0.2518	0.2421	0.0097	0.0001	0.0001
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9615	0.0385	0.0004	0.0004
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0004	0.0090	0.8756	0.8756
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0091	0.8756	0.8756
Absolute Error	0.0003	0.0003	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 1 RFW Total	RCP 1 RFW >130	RCP 1 RFW 130-60	RCP 1 RFW 60-41	RCP 1 RFW <41
	1.4159	1.367	0.0422	0.0006	0.0061
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9655	0.0298	0.0004	0.0043
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0021	0.1459	0.0144
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0023	0.1459	0.0144
Absolute Error	0.0015	0.0015	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 1 RFJ Total	RCP 1 RFJ >130	RCP 1 RFJ 130-60	RCP 1 RFJ 60-41	RCP 1 RFJ <41
	0.2433	0.2431	0.002	0.0001	0.0001
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9992	0.0082	0.0004	0.0004
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0004	0.0004	0.0438	0.8756	0.8756
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0438	0.8756	0.8756
Absolute Error	0.0003	0.0003	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 1 ZW Total	RCP 1 ZW >130	RCP 1 ZW 130-60	RCP 1 ZW 60-41	RCP 1 ZW <41
	0.2569	0.2521	0.0036	0.0003	0.0009
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9813	0.0140	0.0012	0.0035
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0003	0.0243	0.2919	0.0973
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0243	0.2919	0.0973
Absolute Error	0.0003	0.0003	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 1 ZJ Total	RCP 1 ZJ >130	RCP 1 ZJ 130-60	RCP 1 ZJ 60-41	RCP 1 ZJ <41
	1.75	1.67	0.0799	0.0006	0.0002
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9543	0.0457	0.0003	0.0001
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0011	0.1459	0.4378
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0015	0.1459	0.4378
Absolute Error	0.0019	0.0018	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 2 NW Total	RCP 2 NW >130	RCP 2 NW 130-60	RCP 2 NW 60-41	RCP 2 NW <41
	1.1178	0.9494	0.1224	0.0141	0.0319
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.8493	0.1095	0.0126	0.0285
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0007	0.0062	0.0027
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0013	0.0063	0.0029
Absolute Error	0.0012	0.0010	0.0002	0.0001	0.0001

Transferred Soil Weights	RCP 2 NJ Total	RCP 2 NJ >130	RCP 2 NJ 130-60	RCP 2 NJ 60-41	RCP 2 NJ < 41
	0.458	0.3484	0.0941	0.0074	0.0081
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7607	0.2055	0.0162	0.0177
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0002	0.0003	0.0009	0.0118	0.0108
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0014	0.0119	0.0109
Absolute Error	0.0005	0.0004	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 2 RFW Total	RCP 2 RFW >130	RCP 2 RFW 130-60	RCP 2 RFW 60-41	RCP 2 RFW <41
	1.282	1.2022	0.0642	0.0063	0.0093
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9378	0.0501	0.0049	0.0073
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0014	0.0139	0.0094
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0017	0.0139	0.0095
Absolute Error	0.0014	0.0013	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 2 RFJ Total	RCP 2 RFJ >130	RCP 2 RFJ 130-60	RCP 2 RFJ 60-41	RCP 2 RFJ <41
	1.209	0.9487	0.2053	0.0166	0.0384
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7847	0.1698	0.0137	0.0318
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0004	0.0053	0.0023
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0012	0.0054	0.0025
Absolute Error	0.0013	0.0010	0.0002	0.0001	0.0001

Transferred Soil Weights	RCP 2 ZW Total	RCP 2 ZW >130	RCP 2 ZW 130-60	RCP 2 ZW 60-41	RCP 2 ZW <41
	0.1633	0.1304	0.0252	0.0014	0.0063
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7985	0.1543	0.0086	0.0386
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0007	0.0035	0.0625	0.0139
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0013	0.0036	0.0626	0.0139
Absolute Error	0.0002	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 2 ZJ Total	RCP 2 ZJ >130	RCP 2 ZJ 130-60	RCP 2 ZJ 60-41	RCP 2 ZJ <41
	0.0907	0.071	0.0154	0.0022	0.0021
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7828	0.1698	0.0243	0.0232
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0010	0.0012	0.0057	0.0398	0.0417
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0014	0.0016	0.0058	0.0398	0.0417
Absolute Error	0.0001	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 3 NW Total	RCP 3 NW >130	RCP 3 NW 130-60	RCP 3 NW 60-41	RCP 3 NW <41
	0.1537	0.1164	0.0272	0.0026	0.0075
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7573	0.1770	0.0169	0.0488
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0006	0.0008	0.0032	0.0337	0.0117
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0013	0.0034	0.0337	0.0117
Absolute Error	0.0002	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 3 NJ Total	RCP 3 NJ >130	RCP 3 NJ 130-60	RCP 3 NJ 60-41	RCP 3 NJ < 41
	0.2581	0.2139	0.0284	0.0042	0.0116
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.8287	0.1100	0.0163	0.0449
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0004	0.0031	0.0208	0.0075
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0033	0.0209	0.0076
Absolute Error	0.0003	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 3 RFW Total	RCP 3 RFW >130	RCP 3 RFW 130-60	RCP 3 RFW 60-41	RCP 3 RFW <41
	0.5557	0.4512	0.0778	0.0057	0.021
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.8119	0.1400	0.0103	0.0378
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0002	0.0002	0.0011	0.0154	0.0042
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0016	0.0154	0.0043
Absolute Error	0.0006	0.0005	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 3 RFJ Total	RCP 3 RFJ >130	RCP 3 RFJ 130-60	RCP 3 RFJ 60-41	RCP 3 RFJ <41
	0.703	0.5504	0.1178	0.0107	0.0241
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7829	0.1676	0.0152	0.0343
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0002	0.0007	0.0082	0.0036
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0013	0.0083	0.0038
Absolute Error	0.0008	0.0006	0.0002	0.0001	0.0001

Transferred Soil Weights	RCP 3 ZW Total	RCP 3 ZW >130	RCP 3 ZW 130-60	RCP 3 ZW 60-41	RCP 3 ZW <41
	0.1905	0.1751	0.0081	0.0038	0.0035
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.9192	0.0425	0.0199	0.0184
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0005	0.0108	0.0230	0.0250
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0012	0.0109	0.0231	0.0250
Absolute Error	0.0002	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	RCP 3 ZJ Total	RCP 3 ZJ >130	RCP 3 ZJ 130-60	RCP 3 ZJ 60-41	RCP 3 ZJ <41
	0.0592	0.0453	0.0089	0.0015	0.0035
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7652	0.1503	0.0253	0.0591
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0015	0.0019	0.0098	0.0584	0.0250
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0018	0.0022	0.0099	0.0584	0.0250
Absolute Error	0.0001	0.0001	0.0001	0.0001	0.0001

Sherman Circle

	Bulk Soil Sample Average Total	Bulk Soil >130	Bulk Soil 130-60	Bulk Soil 60-41	Bulk Soil < 41
	51.01	26.63	5.67	1.83	16.88
Error in mass= sqrtBfullmass+Bemptyma	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.5221	0.1112	0.0359	0.3309
Error denominator (error of sum of masse	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0000	0.0000	0.0000	0.0000	0.0000
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0011	0.0011
Absolute Error	0.0549	0.0286	0.0061	0.0020	0.0182

Transferred Soil Weights	SH 1 NW Total	SH 1 NW >130	SH 1 NW 130-60	SH 1 NW 60-41	SH 1 NW <41
	1.5518	0.9306	0.3396	0.1552	0.1264
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.5997	0.2188	0.1000	0.0815
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0003	0.0006	0.0007
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0012	0.0013
Absolute Error	0.0017	0.0010	0.0004	0.0002	0.0002

Transferred Soil Weights	SH 1 NJ Total	SH 1 NJ >130	SH 1 NJ 130-60	SH 1 NJ 60-41	SH 1 NJ < 41
	0.2518	0.9048	0.2574	0.0609	0.1032
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	3.5933	1.0222	0.2419	0.4098
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0001	0.0003	0.0014	0.0008
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0018	0.0014
Absolute Error	0.0003	0.0010	0.0003	0.0001	0.0001

Transferred Soil Weights	SH 1 RFW Total	SH 1 RFW >130	SH 1 RFW 130-60	SH 1 RFW 60-41	SH 1 RFW <41
	1.4159	2.006	0.3688	0.0883	0.1087
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	1.4168	0.2605	0.0624	0.0768
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0000	0.0002	0.0010	0.0008
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0015	0.0013
Absolute Error	0.0015	0.0021	0.0004	0.0001	0.0001

Transferred Soil Weights	SH 1 RFJ Total	SH 1 RFJ >130	SH 1 RFJ 130-60	SH 1 RFJ 60-41	SH 1 RFJ <41
	0.2433	1.021	0.3705	0.0588	0.0768
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	4.1965	1.5228	0.2417	0.3157
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0004	0.0001	0.0002	0.0015	0.0011
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0018	0.0016
Absolute Error	0.0003	0.0011	0.0004	0.0001	0.0001

Transferred Soil Weights	SH 1 ZW Total	SH 1 ZW >130	SH 1 ZW 130-60	SH 1 ZW 60-41	SH 1 ZW <41
	0.2569	1.185	0.4002	0.0715	0.0877
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	4.6127	1.5578	0.2783	0.3414
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0001	0.0002	0.0012	0.0010
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0016	0.0015
Absolute Error	0.0003	0.0013	0.0004	0.0001	0.0001

Transferred Soil Weights	SH 1 ZJ Total	SH 1 ZJ >130	SH 1 ZJ 130-60	SH 1 ZJ 60-41	SH 1 ZJ <41
	1.75	1.237	0.1293	0.023	0.1194
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7069	0.0739	0.0131	0.0682
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0007	0.0038	0.0007
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0013	0.0040	0.0013
Absolute Error	0.0019	0.0013	0.0002	0.0001	0.0002

Transferred Soil Weights	SH 2 NW Total	SH 2 NW >130	SH 2 NW 130-60	SH 2 NW 60-41	SH 2 NW <41
	1.1178	1.526	0.311	0.0821	0.3451
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	1.3652	0.2782	0.0734	0.3087
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0001	0.0003	0.0011	0.0003
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0015	0.0011
Absolute Error	0.0012	0.0016	0.0003	0.0001	0.0004

Transferred Soil Weights	SH 2 NJ Total	SH 2 NJ >130	SH 2 NJ 130-60	SH 2 NJ 60-41	SH 2 NJ < 41
	0.458	1.601	0.5819	0.4413	0.2242
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	3.4956	1.2705	0.9635	0.4895
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0002	0.0001	0.0002	0.0002	0.0004
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0011	0.0011
Absolute Error	0.0005	0.0017	0.0006	0.0005	0.0003

Transferred Soil Weights	SH 2 RFW Total	SH 2 RFW >130	SH 2 RFW 130-60	SH 2 RFW 60-41	SH 2 RFW <41
	1.282	3.56	0.3813	0.1825	1.2168
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	2.7769	0.2974	0.1424	0.9491
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0000	0.0002	0.0005	0.0001
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0012	0.0011
Absolute Error	0.0014	0.0038	0.0004	0.0002	0.0013

Transferred Soil Weights	SH 2 RFJ Total	SH 2 RFJ >130	SH 2 RFJ 130-60	SH 2 RFJ 60-41	SH 2 RFJ <41
	1.209	2.963	0.7913	0.1381	0.9259
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	2.4508	0.6545	0.1142	0.7658
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0000	0.0001	0.0006	0.0001
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0012	0.0011
Absolute Error	0.0013	0.0032	0.0009	0.0002	0.0010

Transferred Soil Weights	SH 2 ZW Total	SH 2 ZW >130	SH 2 ZW 130-60	SH 2 ZW 60-41	SH 2 ZW <41
	0.1633	3.16	0.7181	0.1608	0.09
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	19.3509	4.3974	0.9847	0.5511
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0000	0.0001	0.0005	0.0010
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0011	0.0011	0.0012	0.0014
Absolute Error	0.0002	0.0034	0.0008	0.0002	0.0001

Transferred Soil Weights	SH 2 ZJ Total	SH 2 ZJ >130	SH 2 ZJ 130-60	SH 2 ZJ 60-41	SH 2 ZJ <41
	0.0907	1.32	0.776	0.0696	0.2224
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	14.5535	8.5557	0.7674	2.4520
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0010	0.0001	0.0001	0.0013	0.0004
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0014	0.0011	0.0011	0.0017	0.0011
Absolute Error	0.0001	0.0014	0.0008	0.0001	0.0003

Transferred Soil Weights	SH 3 NW Total	SH 3 NW >130	SH 3 NW 130-60	SH 3 NW 60-41	SH 3 NW <41
	0.1537	0.6218	0.3104	0.0414	0.13
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	4.0455	2.0195	0.2694	0.8458
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0006	0.0001	0.0003	0.0021	0.0007
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0011	0.0011	0.0024	0.0013
Absolute Error	0.0002	0.0007	0.0003	0.0001	0.0002

Transferred Soil Weights	SH 3 NJ Total	SH 3 NJ >130	SH 3 NJ 130-60	SH 3 NJ 60-41	SH 3 NJ < 41
	0.2581	0.3976	0.1704	0.0191	0.0568
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	1.5405	0.6602	0.0740	0.2201
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0002	0.0005	0.0046	0.0015
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0012	0.0047	0.0019
Absolute Error	0.0003	0.0004	0.0002	0.0001	0.0001

Transferred Soil Weights	SH 3 RFW Total	SH 3 RFW >130	SH 3 RFW 130-60	SH 3 RFW 60-41	SH 3 RFW <41
	0.5557	1.75	0.0849	0.2276	0.4845
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0004782
s% (mass sample/sum masses)	1.0000	3.1492	0.1528	0.4096	0.871873313
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.000956335
R.E. mass sample (numerator)	0.0002	0.0001	0.0010	0.0004	0.000180721
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.001069215
Total Relative Error	0.0011	0.0011	0.0015	0.0011	0.0011
Absolute Error	0.0006	0.0019	0.0001	0.0003	0.0005

Transferred Soil Weights	SH 3 RFJ Total	SH 3 RFJ >130	SH 3 RFJ 130-60	SH 3 RFJ 60-41	SH 3 RFJ <41
	0.703	3.798	0.4867	0.136	0.5562
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	5.4026	0.6923	0.1935	0.7912
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0000	0.0002	0.0006	0.0002
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0012	0.0011
Absolute Error	0.0008	0.0041	0.0005	0.0002	0.0006

Transferred Soil Weights	SH 3 ZW Total	SH 3 ZW >130	SH 3 ZW 130-60	SH 3 ZW 60-41	SH 3 ZW <41
	0.1905	0.7265	0.7356	0.0435	0.1068
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	3.8136	3.8614	0.2283	0.5606
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0001	0.0001	0.0020	0.0008
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0011	0.0011	0.0023	0.0013
Absolute Error	0.0002	0.0008	0.0008	0.0001	0.0001

Transferred Soil Weights	SH 3 ZJ Total	SH 3 ZJ >130	SH 3 ZJ 130-60	SH 3 ZJ 60-41	SH 3 ZJ <41
	0.0592	0.3179	0.1687	0.026	0.0938
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	5.3699	2.8497	0.4392	1.5845
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0015	0.0003	0.0005	0.0034	0.0009
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0018	0.0011	0.0012	0.0035	0.0014
Absolute Error	0.0001	0.0004	0.0002	0.0001	0.0001

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	Bulk Soil Sample Average Total	Bulk Soil >130	Bulk Soil 130-60	Bulk Soil 60-41	Bulk Soil < 41
	31.89	23.06	2.123	0.6294	5.571
Error in mass= sqrtBfullmass+Bemptyma	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.7231	0.0666	0.0197	0.1747
Error denominator (error of sum of masse	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0000	0.0000	0.0000	0.0001	0.0000
R.E. sum of masses (denominator))	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0011	0.0011	0.0011
Absolute Error	0.0341	0.0247	0.0023	0.0007	0.0060

Transferred Soil Weights	MG 1 NW Total	MG 1 NW >130	MG 1 NW 130-60	MG 1 NW 60-41	MG 1 NW <41
	14.2485	0.0381	0.0114	0.0004	0.0046
Error in mass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0027	0.0008	0.0000	0.0003
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0000	0.0023	0.0077	0.2189	0.0190
R.E. sum of masses (denominator))	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0025	0.0078	0.2189	0.0191
Absolute Error	0.0152	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 1 NJ Total	MG 1 NJ >130	MG 1 NJ 130-60	MG 1 NJ 60-41	MG 1 NJ < 41
	0.2518	0.0266	0.0074	0.0018	0.0029
Error in mass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.1056	0.0294	0.0071	0.0115
Error denominator (error of sum of ı	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0033	0.0118	0.0486	0.0302
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0035	0.0119	0.0487	0.0302
Absolute Error	0.0003	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 1 RFW Total	MG 1 RFW >130	MG 1 RFW 130-60	MG 1 RFW 60-41	MG 1 RFW <41
	1.4159	0.0278	0.0073	0.0022	0.0050
Error in mass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0196	0.0052	0.0016	0.0035
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0031	0.0120	0.0398	0.0175
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0033	0.0120	0.0398	0.0175
Absolute Error	0.0015	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 1 RFJ Total	MG 1 RFJ >130	MG 1 RFJ 130-60	MG 1 RFJ 60-41	MG 1 RFJ <41
	0.2433	0.0304	0.0109	0.0058	0.007
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.1249	0.0448	0.0238	0.0288
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0004	0.0029	0.0080	0.0151	0.0125
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0031	0.0081	0.0151	0.0126
Absolute Error	0.0003	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 1 ZW Total	MG 1 ZW >130	MG 1 ZW 130-60	MG 1 ZW 60-41	MG 1 ZW <41
	0.2569	0.0136	0.0034	0.0007	0.0015
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0529	0.0132	0.0027	0.0058
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0064	0.0258	0.1251	0.0584
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0065	0.0258	0.1251	0.0584
Absolute Error	0.0003	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 1 ZJ Total	MG 1 ZJ >130	MG 1 ZJ 130-60	MG 1 ZJ 60-41	MG 1 ZJ <41
	1.750	0.0097	0.0042	0.0015	0.0013
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0055	0.0024	0.0009	0.0007
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0090	0.0208	0.0584	0.0674
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0091	0.0209	0.0584	0.0674
Absolute Error	0.0019	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 2 NW Total	MG 2 NW >130	MG 2 NW 130-60	MG 2 NW 60-41	MG 2 NW <41
	1.1178	0.4553	0.1291	0.0289	0.0480
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.4073	0.1155	0.0259	0.0429
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0002	0.0007	0.0030	0.0018
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0013	0.0032	0.0021
Absolute Error	0.0012	0.0005	0.0002	0.0001	0.0001

Transferred Soil Weights	MG 2 NJ Total	MG 2 NJ >130	MG 2 NJ 130-60	MG 2 NJ 60-41	MG 2 NJ < 41
	0.458	0.209	0.0384	0.0083	0.008
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.4563	0.0838	0.0181	0.0175
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0002	0.0004	0.0023	0.0105	0.0109
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0025	0.0106	0.0110
Absolute Error	0.0005	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 2 RFW Total	MG 2 RFW >130	MG 2 RFW 130-60	MG 2 RFW 60-41	MG 2 RFW <41
	1.282	0.4107	0.0356	0.0065	0.01
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.3204	0.0278	0.0051	0.0078
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0002	0.0025	0.0135	0.0088
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0011	0.0027	0.0135	0.0088
Absolute Error	0.0014	0.0004	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 2 RFJ Total	MG 2 RFJ >130	MG 2 RFJ 130-60	MG 2 RFJ 60-41	MG 2 RFJ <41
	1.209	0.1461	0.0431	0.0099	0.018
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.1208	0.0356	0.0082	0.0149
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0006	0.0020	0.0088	0.0049
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0012	0.0023	0.0089	0.0050
Absolute Error	0.0013	0.0002	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 2 ZW Total	MG 2 ZW >130	MG 2 ZW 130-60	MG 2 ZW 60-41	MG 2 ZW <41
	0.1633	0.3015	0.0446	0.0067	0.0135
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	1.8463	0.2731	0.0410	0.0827
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0003	0.0020	0.0131	0.0065
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0011	0.0022	0.0131	0.0066
Absolute Error	0.0002	0.0003	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 2 ZJ Total	MG 2 ZJ >130	MG 2 ZJ 130-60	MG 2 ZJ 60-41	MG 2 ZJ <41
	0.0907	0.097	0.0468	0.0061	0.0408
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	1.0695	0.5160	0.0673	0.4498
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0010	0.0009	0.0019	0.0144	0.0021
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0014	0.0014	0.0022	0.0144	0.0024
Absolute Error	0.0001	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 3 NW Total	MG 3 NW >130	MG 3 NW 130-60	MG 3 NW 60-41	MG 3 NW <41
	0.1537	0.0114	0.01	0.0034	0.0086
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0742	0.0651	0.0221	0.0560
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0006	0.0077	0.0088	0.0258	0.0102
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0078	0.0088	0.0258	0.0102
Absolute Error	0.0002	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	SH 3 NJ Total	MG 3 NJ >130	MG 3 NJ 130-60	MG 3 NJ 60-41	MG 3 NJ < 41
	0.2581	0.0364	0.0196	0.0052	0.0072
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.1410	0.0759	0.0201	0.0279
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0003	0.0024	0.0045	0.0168	0.0122
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0026	0.0046	0.0169	0.0122
Absolute Error	0.0003	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 3 RFW Total	MG 3 RFW >130	MG 3 RFW 130-60	MG 3 RFW 60-41	MG 3 RFW <41
	0.5557	0.1309	0.004	0.0026	0.0042
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.2356	0.0072	0.0047	0.0076
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0002	0.0007	0.0219	0.0337	0.0208
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0013	0.0219	0.0337	0.0209
Absolute Error	0.0006	0.0002	0.0001	0.0001	0.0001

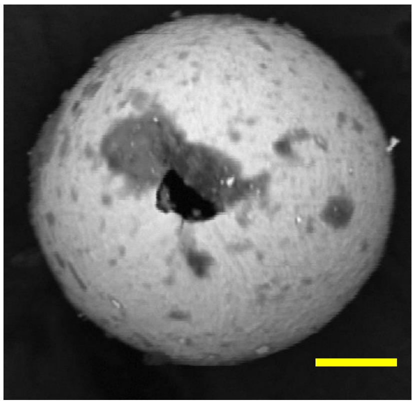
Transferred Soil Weights	MG 3 RFJ Total	MG 3 RFJ >130	MG 3 RFJ 130-60	MG 3 RFJ 60-41	MG 3 RFJ <41
	0.703	0.0188	0.0077	0.0016	0.0084
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0267	0.0110	0.0023	0.0119
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0001	0.0047	0.0114	0.0547	0.0104
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0011	0.0048	0.0114	0.0547	0.0105
Absolute Error	0.0008	0.0001	0.0001	0.0001	0.0001

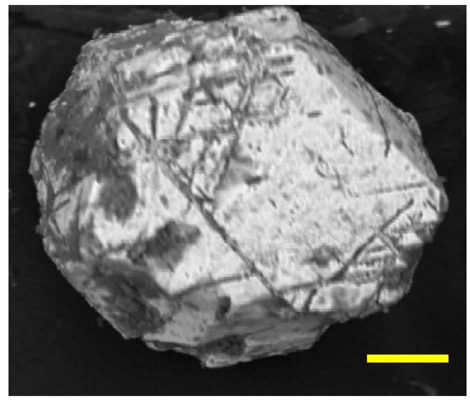
Transferred Soil Weights	MG 3 ZW Total	MG 3 ZW >130	MG 3 ZW 130-60	MG 3 ZW 60-41	MG 3 ZW <41
	0.1905	0.0025	0.0024	0.0009	0.0041
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.0131	0.0126	0.0047	0.0215
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0005	0.0350	0.0365	0.0973	0.0214
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0012	0.0350	0.0365	0.0973	0.0214
Absolute Error	0.0002	0.0001	0.0001	0.0001	0.0001

Transferred Soil Weights	MG 3 ZJ Total	MG 3 ZJ >130	MG 3 ZJ 130-60	MG 3 ZJ 60-41	MG 3 ZJ <41
	0.0592	0.0276	0.0063	0.0037	0.0081
Error in mass= sqrtBfullmass+Bemptymass	0.0005	0.0005	0.0005	0.0005	0.0005
s% (mass sample/sum masses)	1.0000	0.4662	0.1064	0.0625	0.1368
Error denominator (error of sum of masses)	0.0010	0.0010	0.0010	0.0010	0.0010
R.E. mass sample (numerator)	0.0015	0.0032	0.0139	0.0237	0.0108
R.E. sum of masses (denominator)	0.0011	0.0011	0.0011	0.0011	0.0011
Total Relative Error	0.0018	0.0033	0.0139	0.0237	0.0109
Absolute Error	0.0001	0.0001	0.0001	0.0001	0.0001

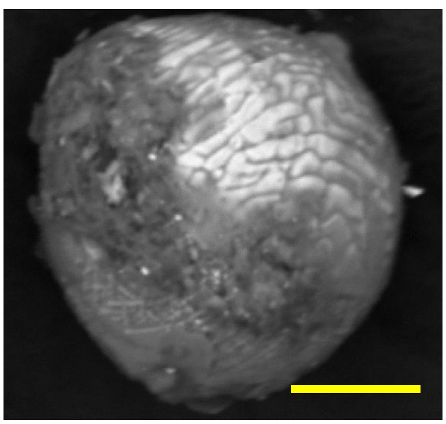
Appendix 8: Additional Scanning Electron Microscopy (SEM) and Backscatter Electron (BSE) Images of the Heavy and Magnetic Mineral Fractions

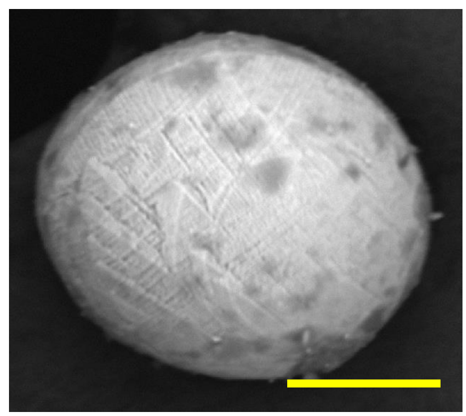
Rock Creek Park



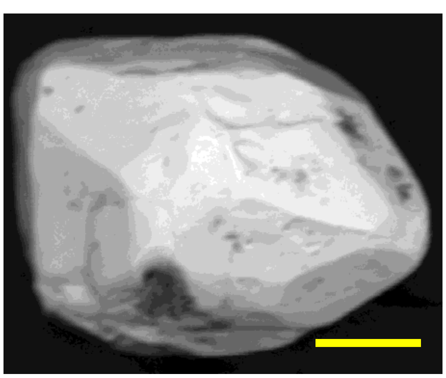


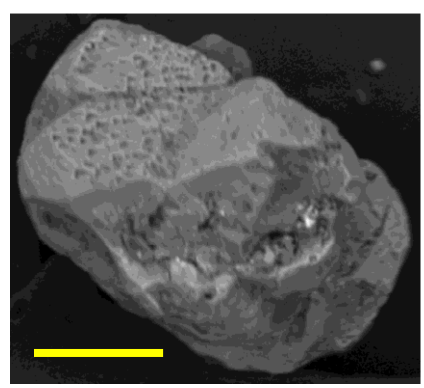
Iron oxide sphere with smooth texture (left) and iron oxide with hatch marks (right). Scale bars are 20 µm.



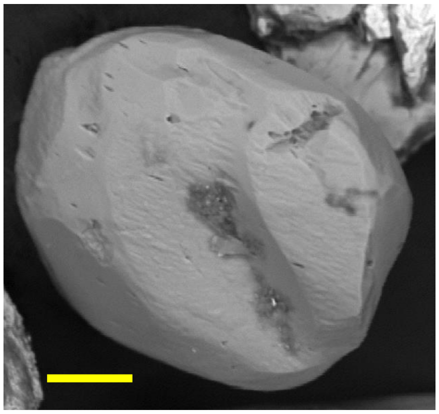
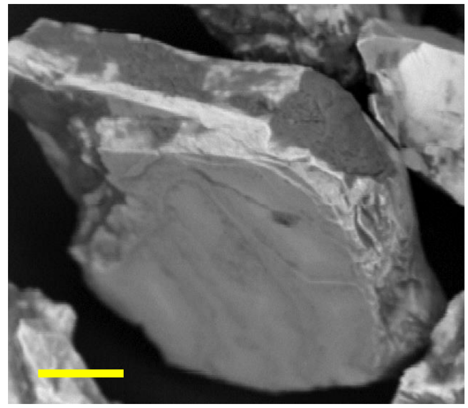


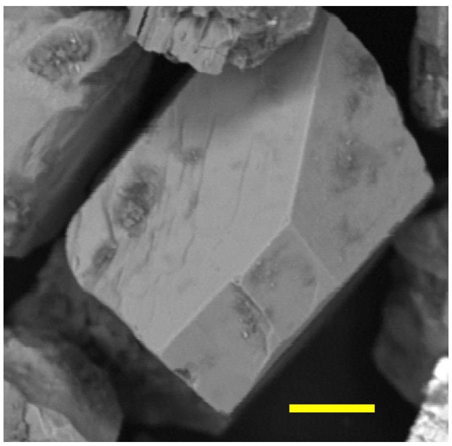
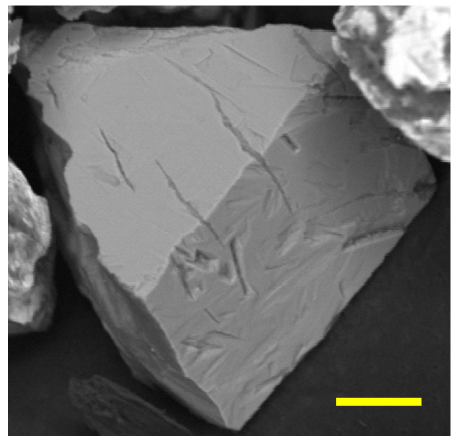
Iron oxide spheres with myrmekitic (left) and dendritic (right) textures. Scale bars are 20 µm.

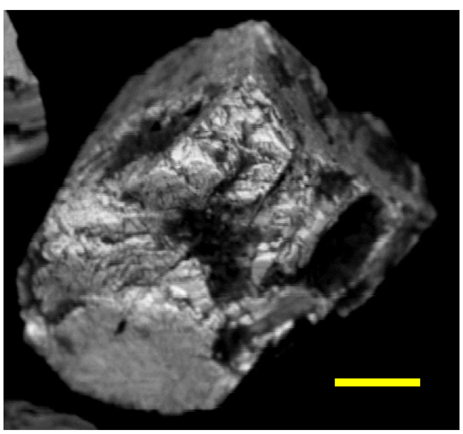
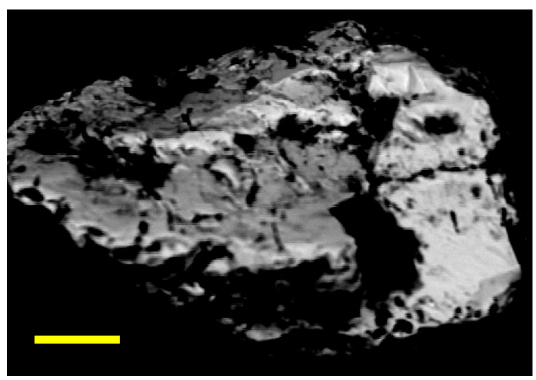


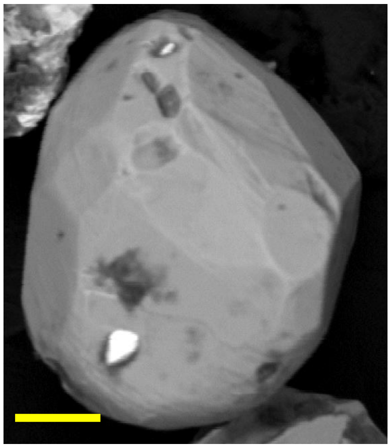
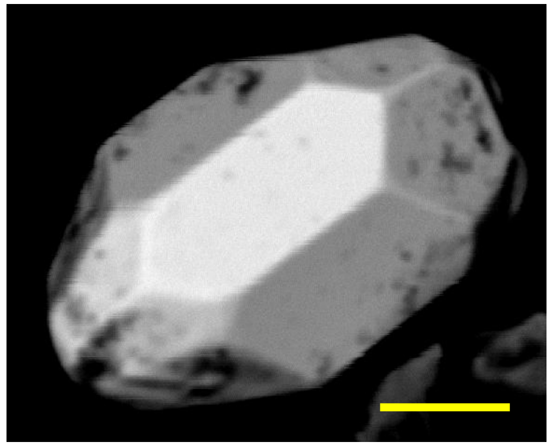


Anhedral zircon (left) and subhedral pitted epidote (right). Scale bars are 20 µm.

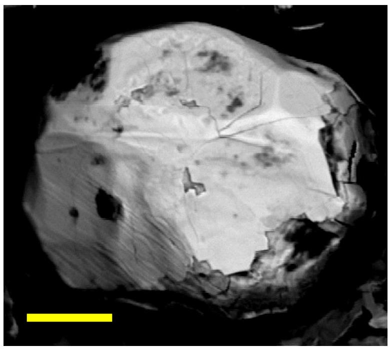
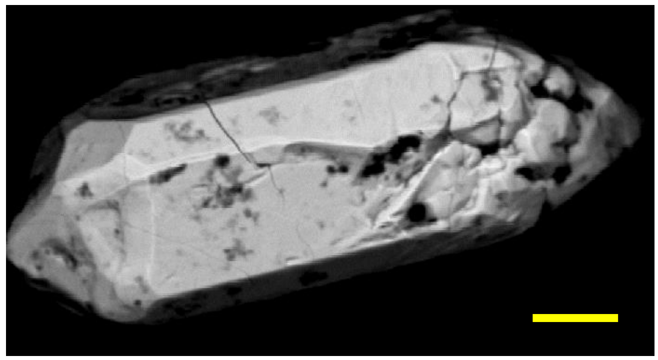


Anhedral apatite (left) and subhedral ilmenite (right). Scale bars are 20 µm.



Euhedral fractured garnet (left) & subhedral fractured garnet (right).Scale bars 20 µm.

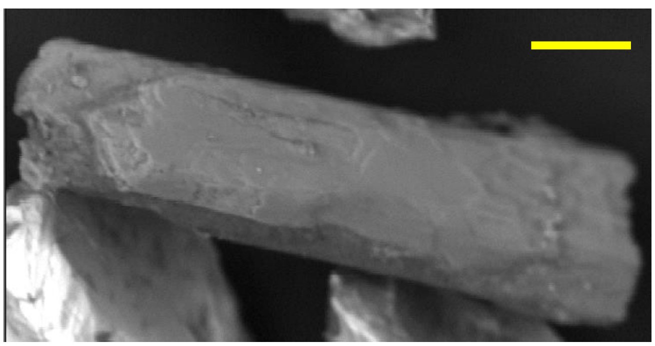


Anhedral scratched magnetite (left) and anhedral monazite (right). Scale bars 20 µm.

Subhedral rutile (left) and subhedral zircon (right). Scale bars are 20 µm.

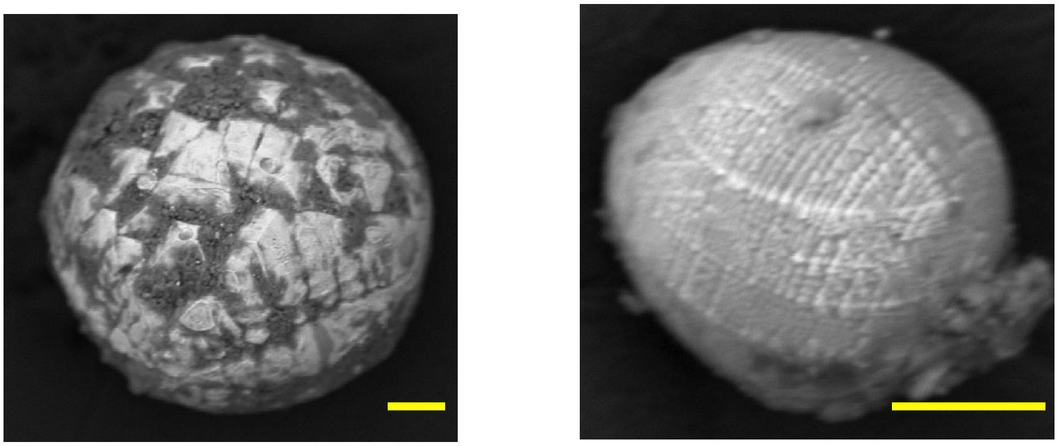



Anhedral, rounded zircon (left) and euhedral zircon (right). Scale bars are 20 µm.

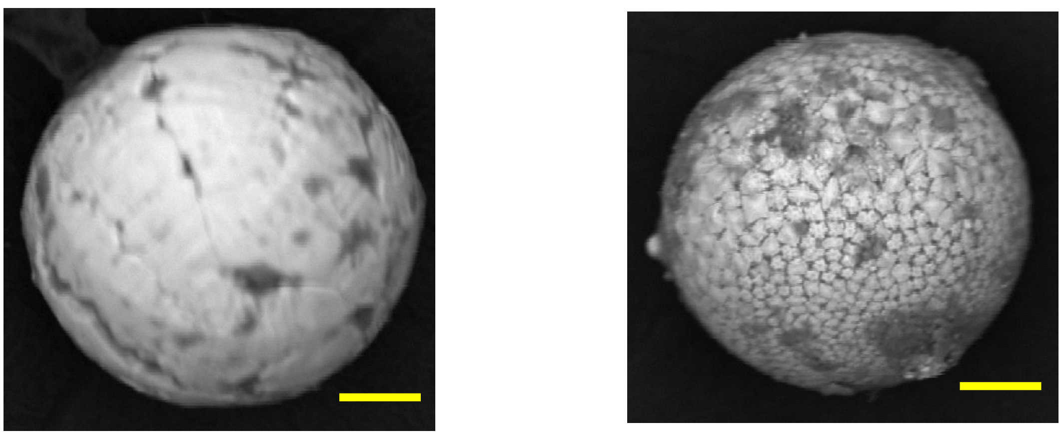


Subhedral elongate epidote. Scale bar is 20 µm.

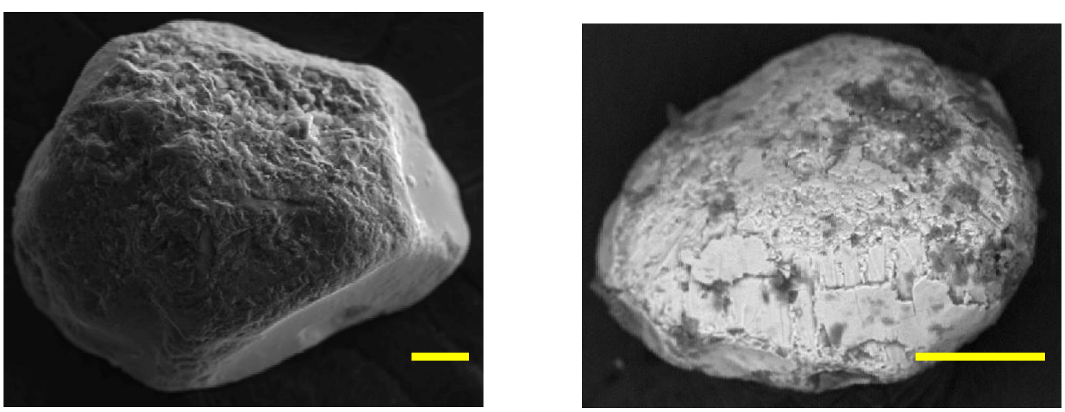
Marvin Gaye Park



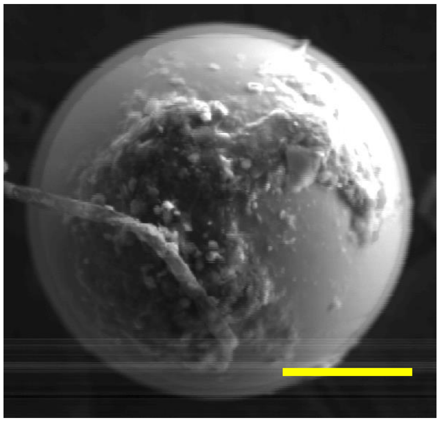
Iron oxide spheres with blocky (left) and dendritic (right) textures. Scale bars are 20 μm.

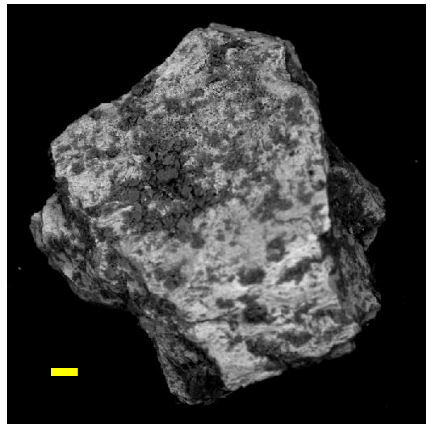


Iron oxide spheres with cracked textures. Scale bars are 20 μm.



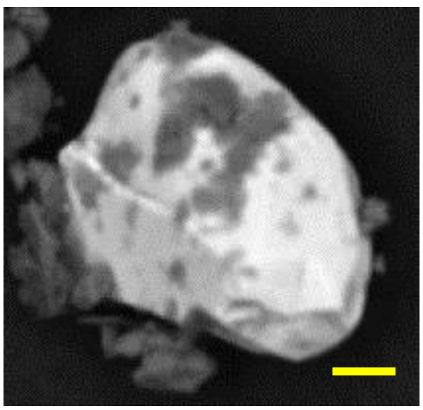
Rounded hematite (left) and rounded ilmenite (right). Scale bars are 20 μm.

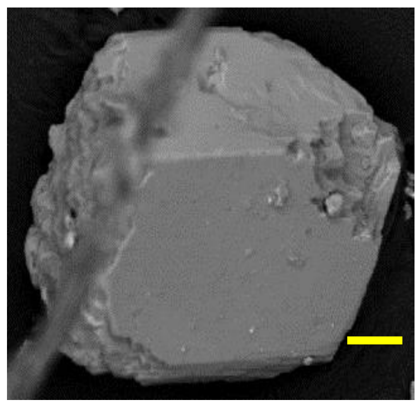




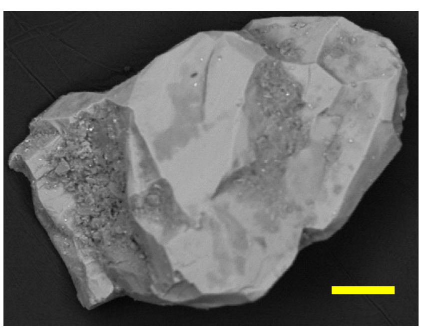
Titanium dioxide sphere (left) and anhedral magnetite (right). Scale bars are 20 μm.

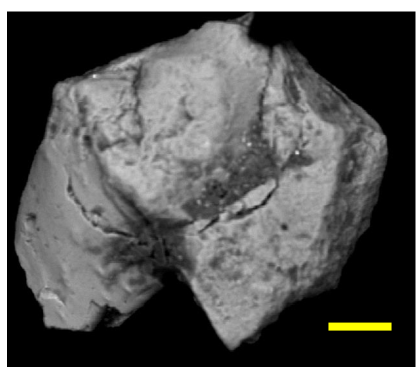
Sherman Circle



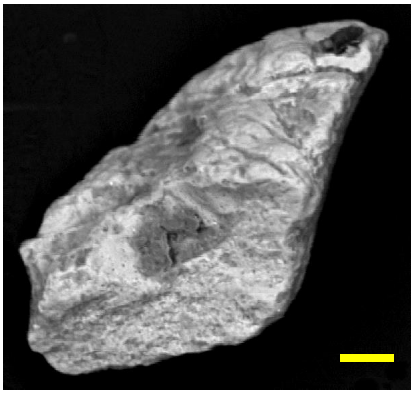


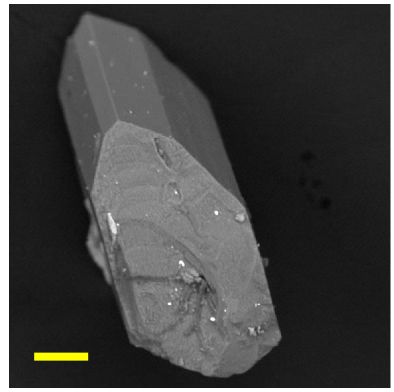
Subhedral zircon (left) and subhedral fractured garnet (right). Scale bars are 20 μm.



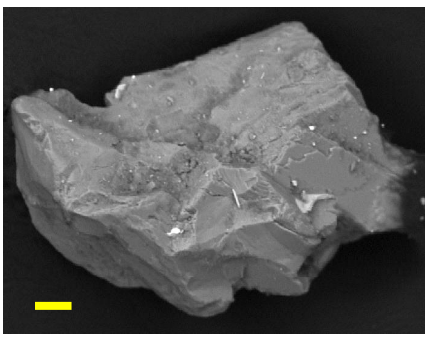


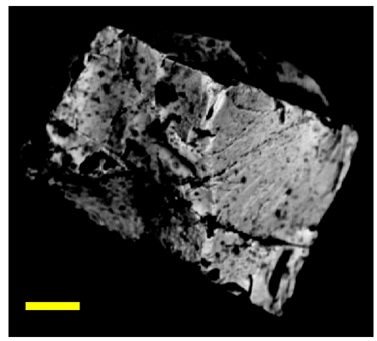
Subhedral diopside (left) and subhedral, scratched hematite (right). Scale bars 20 μm.



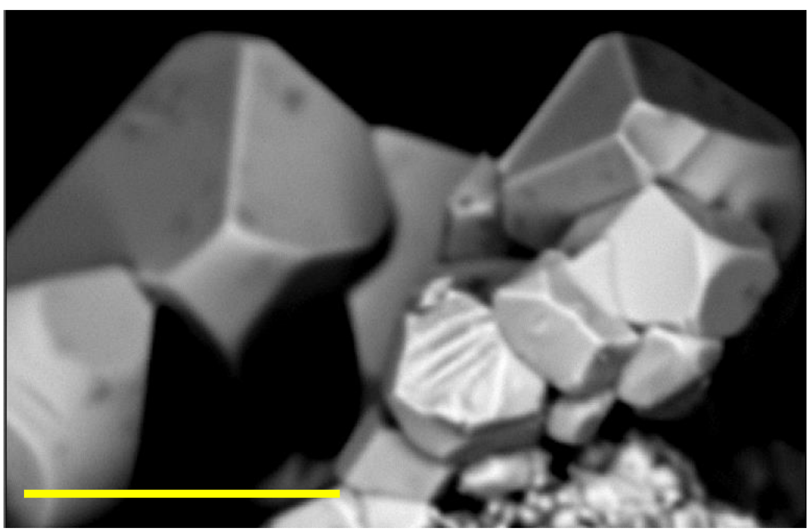


Anhedral, scratched and pitted ilmenite (left) and euhedral tourmaline (right). Scale bars are 20 μm.





Subhedral, fractured epidote (left) and subhedral monazite (right). Scale bars 20 μm.



Euhedral magnetite cluster. Note the small size of the crystals relative to those in the other figures in this Appendix. Scale bar is 20 μm.

Appendix 9: Additional Particle Size Distribution Statistical Analysis

The following three tables show the outcomes of the t-test comparing the control and transferred soil samples for the three sample locations, using the log-transform of the original particle sizes. Performing a log-transform can sometimes "normalize" data that otherwise does not fit a normal distribution, but in this case, there were no significant differences in the results. These tables can be compared to Tables 8-10 in Chapter 6.

Rock Creek Park				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	5.0480	15.729	0.1463	54.339
Transfer 1 NJ	3.7481	1.986	0.1651	29.788
Transfer 1 RFW	3.8944	3.130	0.1327	15.271
Transfer 1 RFJ	5.1077	8.876	0.1480	29.579
Transfer 1 ZW	4.4701	6.496	0.3748	16.531
Transfer 1 ZJ	3.4827	1.228	0.2387	37.373
Transfer 2 NW	0.6353	2.674	1.5660	3.758
Transfer 2 NJ	4.5319	5.481	1.6900	6.672
Transfer 2 RFW	2.8650	0.815	1.0941	12.098
Transfer 2 RFJ	3.4339	4.631	1.6085	3.106
Trnasfer 2 ZW	2.8162	4.205	1.3727	1.922
Transfer 2 ZJ	3.4414	4.582	1.8944	5.018
Transfer 3 NW	4.689	4.816	1.7129	0.492
Transfer 3 NJ	1.503	2.695	1.6935	0.993
Transfer 3 RFW	2.227	3.770	1.4625	16.069
Transfer 3 RFJ	3.514	4.573	1.6601	2.642
Transfer 3 ZW	2.157	1.545	1.7955	6.440
Transfer 3 ZJ	4.323	4.087	1.9152	1.6583
t critical	**2.5706**	**two-tailed 95% CI**		

Sherman Circle				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	2.25	6.809	8.539	11.096
Transfer 1 NJ	4.23	5.597	1.988	11.489
Transfer 1 RFW	6.36	2.639	0.426	16.409
Transfer 1 RFJ	3.95	7.828	0.534	15.002
Transfer 1 ZW	4.20	7.274	1.057	15.006
Transfer 1 ZJ	7.15	2.441	7.235	11.327
Transfer 2 NW	2.31	7.280	0.918	6.936
Transfer 2 NJ	2.38	2.680	12.823	10.781
Transfer 2 RFW	2.75	2.230	1.088	3.364
Transfer 2 RFJ	2.88	3.169	1.813	4.019
Trnasfer 2 ZW	5.85	5.171	0.513	21.886
Transfer 2 ZJ	4.37	3.810	0.019	8.253
Transfer 3 NW	3.40	4.706	1.453	7.009
Transfer 3 NJ	4.94	3.215	0.459	9.297
Transfer 3 RFW	2.09	4.025	6.366	5.413
Transfer 3 RFJ	5.26	2.453	2.752	8.930
Transfer 3 ZW	4.56	3.802	1.184	9.262
Transfer 3 ZJ	2.46	3.917	2.675	4.704
t critical	**2.5706**	**two-tailed 95% CI**		

Marvin Gaye Park				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	0.57275	7.03448	4.56455	1.46894
Transfer 1 NJ	0.89442	6.51393	4.81638	1.82086
Transfer 1 RFW	1.74544	5.91927	5.38399	0.47279
Transfer 1 RFJ	4.71947	6.81713	9.05903	0.20534
Transfer 1 ZW	0.32316	6.06875	3.57910	1.69757
Transfer 1 ZJ	4.09085	8.10294	8.15994	1.70821
Transfer 2 NW	0.85108	6.63770	4.50287	1.93810
Transfer 2 NJ	1.10351	4.71861	2.64330	4.60544
Transfer 2 RFW	3.95242	1.23258	1.26838	5.47023
Transfer 2 RFJ	1.32198	6.72351	4.70892	1.47690
Trnasfer 2 ZW	2.52779	3.89670	0.07474	3.91976
Transfer 2 ZJ	6.61049	7.96091	2.91442	1.28211
Transfer 3 NW	14.18512	9.11394	8.79584	1.82996
Transfer 3 NJ	5.75256	8.85954	7.31265	0.81571
Transfer 3 RFW	4.71889	4.57903	0.09071	4.56414
Transfer 3 RFJ	6.37249	7.08374	4.51533	1.49785
Transfer 3 ZW	19.90574	7.88989	8.22115	3.23560
Transfer 3 ZJ	3.35038	4.61671	7.63247	0.72543
tcritical	**2.5706**	**two-tailed 95% CI**		

The following six tables show the results of the t-test of particle size distributions between the control soil and the transferred soil from the “incorrect” location. These calculations were performed in order to determine if the soil collected from a shoe could match an inappropriate location, yielding a false positive identification in forensic analyses (e.g. a transferred sample from Marvin Gaye Park more closely matched the whole soil from Rock Creek Park, and so on).

Rock Creek Park Control Soil, Marvin Gaye Park Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	6.85429	10.95591	0.58634	2.80021
Transfer 1 NJ	7.33517	9.56847	10.51617	1.84110
Transfer 1 RFW	8.56882	8.12867	12.07441	6.22400
Transfer 1 RFJ	12.47057	10.36141	27.71950	7.35717
Transfer 1 ZW	6.47550	8.47681	7.66678	2.16420
Transfer 1 ZJ	11.69602	14.22543	22.79110	2.13577
Transfer 2 NW	7.27086	9.88715	9.72728	1.54609
Transfer 2 NJ	4.21210	5.63518	5.92847	2.78879
Transfer 2 RFW	0.84987	0.73791	1.31333	3.53941
Transfer 2 RFJ	7.96188	10.11214	10.24027	2.77721
Trnasfer 2 ZW	1.77633	4.20280	2.51765	2.01631
Transfer 2 ZJ	14.65181	13.75532	6.39960	15.92268
Transfer 3 NW	21.50365	17.92614	26.18546	20.33277
Transfer 3 NJ	13.68909	16.93334	18.88065	4.91320
Transfer 3 RFW	2.34647	3.02256	2.53397	2.74716
Transfer 3 RFJ	14.38908	11.09377	9.75772	17.56250
Transfer 3 ZW	25.13940	13.52454	23.09968	36.20153
Transfer 3 ZJ	10.75013	5.44637	20.28062	12.20451
tcritical	**2.5706**	**two-tailed 95% CI**		

Rock Creek Park Control Soil, Sherman Circle Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	10.92	11.703	25.680	2.501
Transfer 1 NJ	7.62	9.749	10.312	2.111
Transfer 1 RFW	3.54	5.877	7.067	1.467
Transfer 1 RFJ	8.10	13.541	8.247	0.655
Transfer 1 ZW	7.66	12.518	8.949	0.657
Transfer 1 ZJ	1.91	1.419	1.655	2.269
Transfer 2 NW	10.83	12.529	6.512	8.040
Transfer 2 NJ	10.72	5.923	44.577	2.829
Transfer 2 RFW	10.13	5.427	6.328	15.684
Transfer 2 RFJ	9.91	6.488	5.583	14.017
Trnasfer 2 ZW	4.58	9.116	8.220	3.572
Transfer 2 ZJ	7.37	7.272	7.597	5.971
Transfer 3 NW	9.06	8.458	9.511	7.916
Transfer 3 NJ	6.32	6.542	7.028	4.554
Transfer 3 RFW	11.18	7.547	19.210	10.894
Transfer 3 RFJ	5.72	5.671	4.709	5.031
Transfer 3 ZW	7.03	7.262	9.126	4.598
Transfer 3 ZJ	10.60	7.409	11.421	12.414
t critical	**2.5706**	**two-tailed 95% CI**		

Sherman Circle Control Soil & Rock Creek Park Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	13.3379	10.616	7.6585	8.600
Transfer 1 NJ	12.3215	7.091	7.7299	8.590
Transfer 1 RFW	12.4340	7.927	7.7243	8.489
Transfer 1 RFJ	13.3855	9.997	7.7270	8.589
Transfer 1 ZW	12.8814	9.441	7.5693	8.509
Transfer 1 ZJ	12.1186	6.407	7.7412	8.597
Transfer 2 NW	9.1571	0.284	5.1846	7.862
Transfer 2 NJ	6.6554	8.918	4.4465	8.143
Transfer 2 RFW	11.6520	5.983	6.7888	8.412
Transfer 2 RFJ	7.3327	5.499	4.9521	7.778
Trnasfer 2 ZW	7.7230	4.013	6.0265	7.602
Transfer 2 ZJ	7.3279	5.321	2.7481	8.000
Transfer 3 NW	6.5600	6.186	4.2884	7.338
Transfer 3 NJ	8.5758	0.233	4.4224	7.437
Transfer 3 RFW	8.1017	2.641	5.6756	8.502
Transfer 3 RFJ	7.2828	5.284	4.6416	7.713
Transfer 3 ZW	11.1273	6.708	3.6568	8.125
Transfer 3 ZJ	6.7825	3.632	2.5338	7.071
t critical	**2.5706**	**two-tailed 95% CI**		

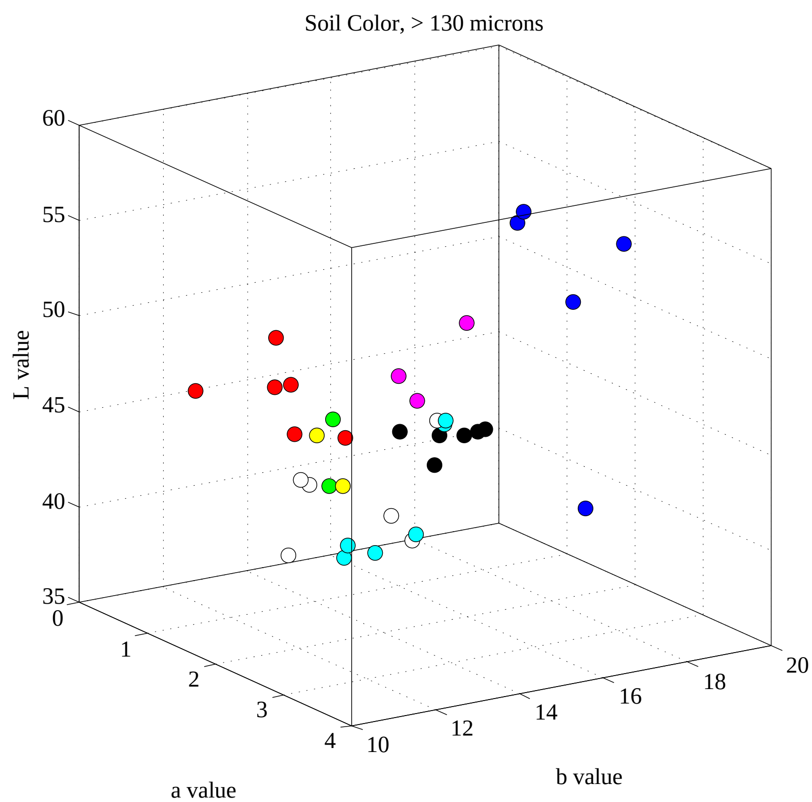
Sherman Circle Control Soil & Marvin Gaye Park Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	4.91652	9.27407	6.28354	6.41663
Transfer 1 NJ	4.58510	7.55176	1.87745	6.66156
Transfer 1 RFW	3.73485	5.76445	3.02285	5.54228
Transfer 1 RFJ	1.04574	8.53608	14.52289	5.25289
Transfer 1 ZW	5.17759	6.19661	0.21702	6.57905
Transfer 1 ZJ	1.57957	13.33274	10.90023	6.58631
Transfer 2 NW	4.62942	7.94736	1.29757	6.73690
Transfer 2 NJ	6.73754	2.66912	1.49478	7.84392
Transfer 2 RFW	10.22628	3.41015	4.88717	8.03561
Transfer 2 RFJ	4.15316	8.22665	1.67464	6.42250
Trnasfer 2 ZW	8.41629	0.89103	4.00193	7.64665
Transfer 2 ZJ	0.45758	12.74916	1.14847	3.06547
Transfer 3 NW	5.17992	17.92666	13.39528	1.93924
Transfer 3 NJ	0.20593	16.69422	8.02582	5.87702
Transfer 3 RFW	11.25775	8.07826	3.98993	7.83329
Transfer 3 RFJ	0.27651	9.44521	1.31994	2.64670
Transfer 3 ZW	7.68571	12.46268	11.12705	2.11325
Transfer 3 ZJ	2.23148	2.43475	9.05488	4.01500
tcritical	**2.5706**	**two-tailed 95% CI**		

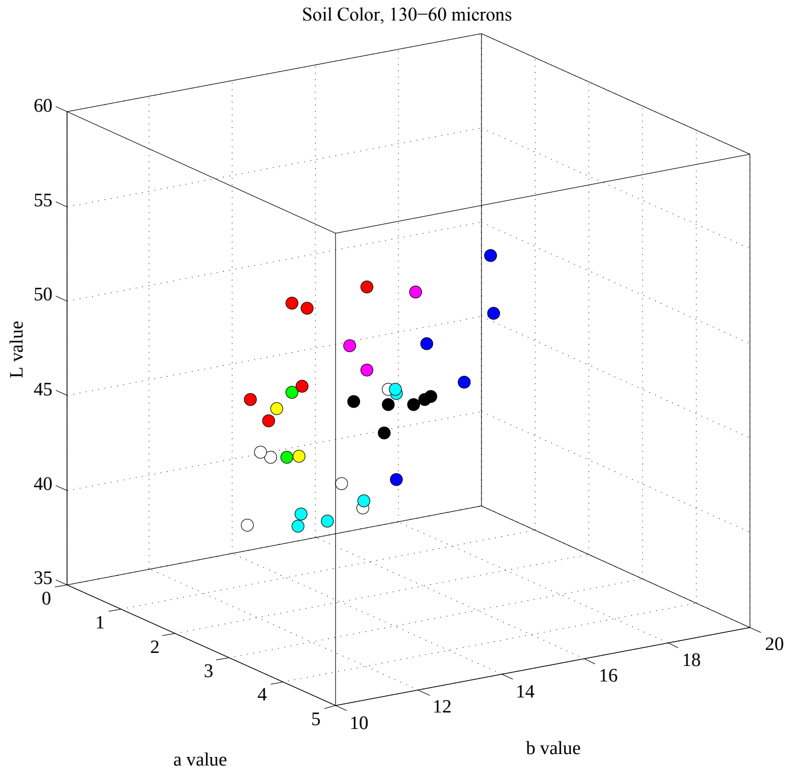
Marvin Gaye Park Control Soil, Rock Creek Park Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	7.1299	6.425	6.8558	4.532
Transfer 1 NJ	6.1858	2.777	6.9812	4.521
Transfer 1 RFW	6.2903	3.642	6.9715	4.418
Transfer 1 RFJ	7.1741	5.784	6.9762	4.521
Transfer 1 ZW	6.7059	5.209	6.6993	4.439
Transfer 1 ZJ	5.9973	2.068	7.0011	4.529
Transfer 2 NW	3.2466	4.268	2.5115	3.778
Transfer 2 NJ	0.9228	13.793	1.2152	4.064
Transfer 2 RFW	5.5640	1.630	5.3286	4.340
Transfer 2 RFJ	1.5519	10.254	2.1031	3.692
Trnasfer 2 ZW	1.9145	8.717	3.9899	3.512
Transfer 2 ZJ	1.5475	10.070	1.7673	3.919
Transfer 3 NW	0.8343	10.965	0.9376	3.242
Transfer 3 NJ	2.7066	4.321	1.1730	3.344
Transfer 3 RFW	2.2663	7.296	3.3738	4.432
Transfer 3 RFJ	1.5056	10.032	1.5580	3.626
Transfer 3 ZW	5.0766	2.380	0.1715	4.046
Transfer 3 ZJ	1.0409	8.322	2.1436	2.969
t critical	**2.5706**	**two-tailed 95% CI**		

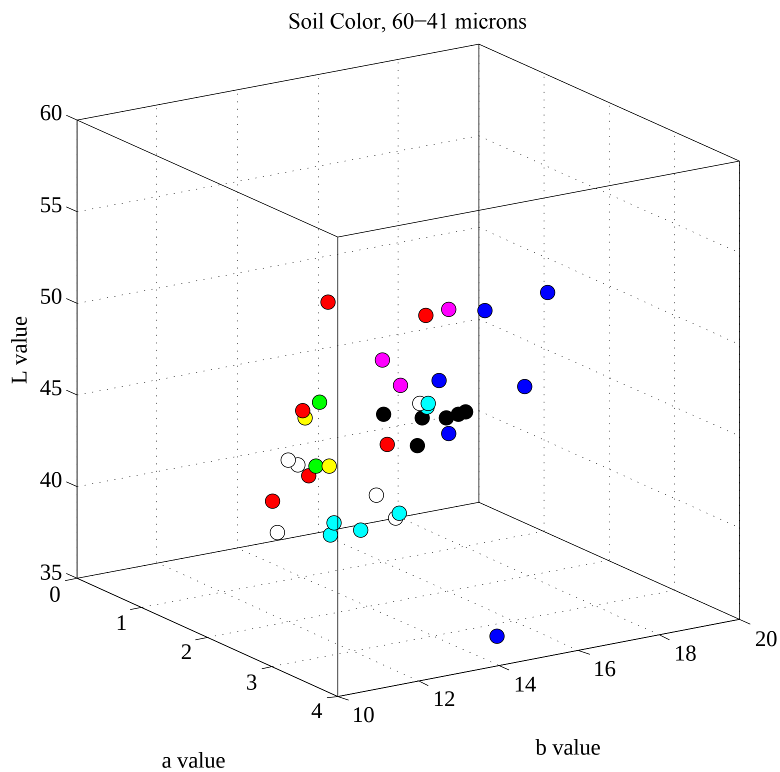
Marvin Gaye Park Control Soil, Sherman Circle Shoes				
	t statistic >130	**t statistic 130-60**	**t statistic 60-41**	**t statistic < 41**
Transfer 1 NW	3.30	15.121	29.464	2.379
Transfer 1 NJ	1.18	12.611	9.627	2.481
Transfer 1 RFW	1.43	7.636	5.437	3.415
Transfer 1 RFJ	1.49	17.483	6.962	3.203
Transfer 1 ZW	1.21	16.168	7.868	3.203
Transfer 1 ZJ	2.47	1.909	1.548	2.440
Transfer 2 NW	3.24	16.183	4.722	0.934
Transfer 2 NJ	3.17	7.695	53.857	2.294
Transfer 2 RFW	2.79	7.058	4.484	1.060
Transfer 2 RFJ	2.65	8.422	3.522	0.625
Trnasfer 2 ZW	0.77	11.798	6.926	3.964
Transfer 2 ZJ	1.02	9.429	6.121	1.474
Transfer 3 NW	2.10	10.952	8.592	0.966
Transfer 3 NJ	0.35	8.491	5.388	1.844
Transfer 3 RFW	3.46	9.782	21.112	0.190
Transfer 3 RFJ	0.03	7.371	2.395	1.719
Transfer 3 ZW	0.80	9.416	8.096	1.832
Transfer 3 ZJ	3.09	9.604	11.058	0.207
t critical	**2.5706**	**two-tailed 95% CI**		

Appendix 10: Additional Soil Color Plots

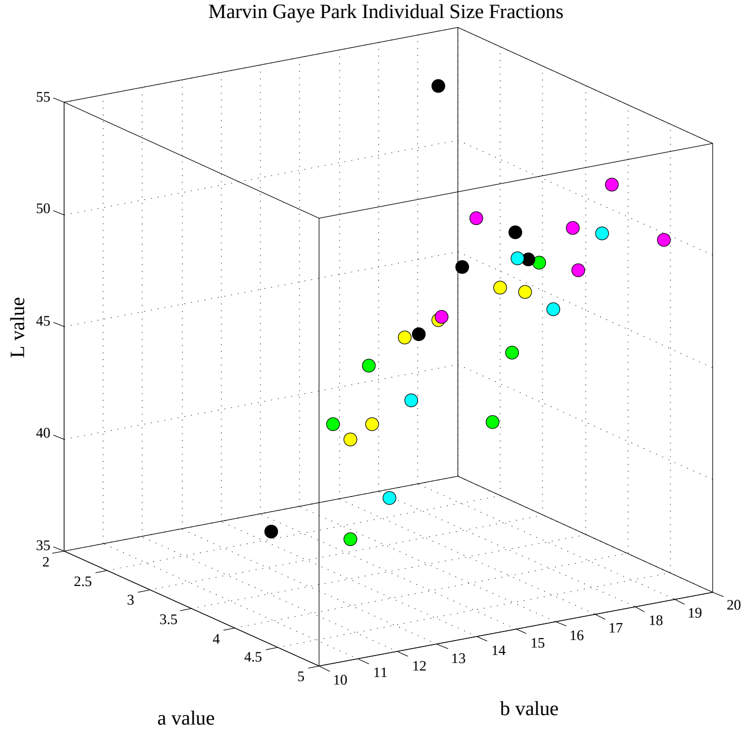
The following soil color plots compare the undisturbed and transferred soil material for Rock Creek Park and Sherman Circle. Each plot represents the color measuremtns from a certain size fraction (labeled on respective plots). For each of the plots, the color scheme is as follows: Rock Creek Park undisturbed soil (red); RCP Transfer 1 (magenta); RCP Transfer 2 (green); RCP Transfer 3 (yellow); Sherman Circle undisturbed soil (blue); SHC Transfer 1 (cyan); SHC Transfer 2 (white); SHC Transfer 3 (black).



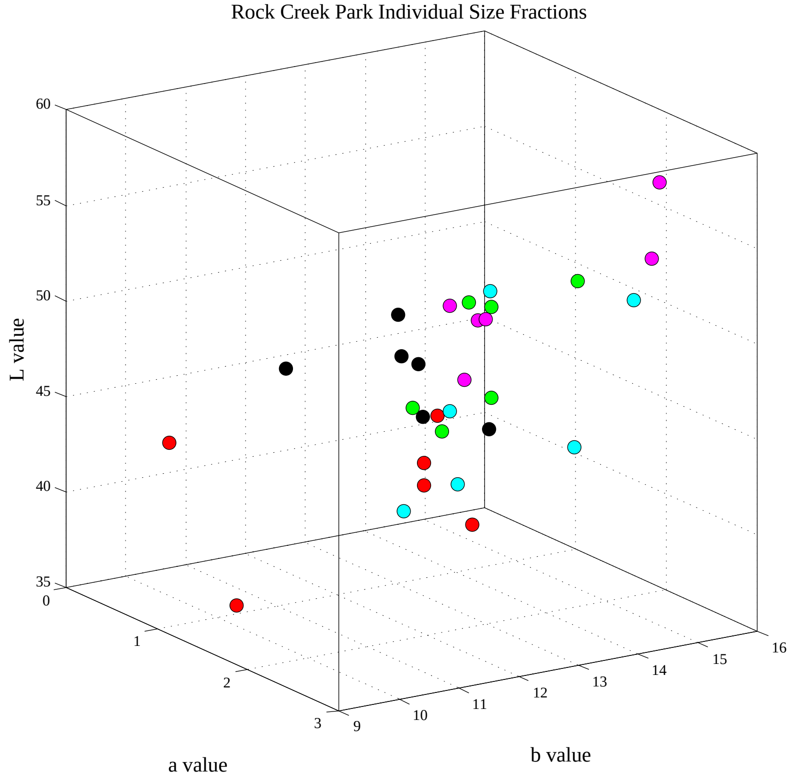

Soil Color, 130−60 microns
L value
a value
b value
60
55
50
45
40
35
0
1
2
3
4
5
10
12
14
16
18
20

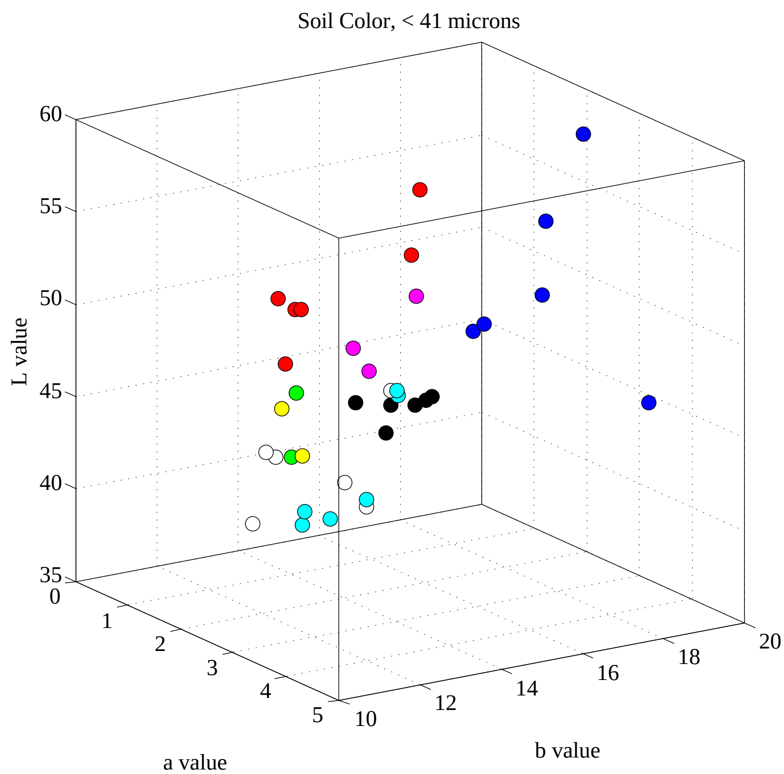

Soil Color, 60−41 microns
L value
a value
b value
60
55
50
45
40
35
0
1
2
3
4
10
12
14
16
18
20

Marvin Gaye Park Individual Size Fractions



Rock Creek Park Individual Size Fractions




Soil Color, < 41 microns
L value
60
55
50
45
40
35
0
1
2
3
4
5
a value
10
12
14
16
18
20
b value

Appendix 11: Shoe Tread Gap Measurements

As part of the characterization of the shoes used in this study, tread gap distributions were calculated. First, each tread gap was measured according to its width (the narrower dimension), and assigned a corresponding bin. The bins were created in 1-mm increments (e.g. a 1.2 and 1.8 mm tread gap would both be assigned to the 1-mm bin). The total linear length of all tread gaps was calculated, allowing for the expression of each tread gap size bin as a percentage of the total tread gap length. The following three tables show the tread gap measurements for the three pairs of shoes used in this study.

Nike Air Pegasus		
Tread Gap Width (mm)	Length (mm)	Percentage
< 1.0	0	0.00
1.0-1.9	241	15.19
2.0-2.9	200	12.60
3.0-3.9	268	16.89
4.0-4.9	261	16.45
5.0-5.9	268	16.89
6.0-6.9	230	14.49
7.0-7.9	42	2.65
8.0-8.9	10	0.63
9.0-9.9	0	0.00
10.0-10.9	12	0.76
11.0-11.9	0	0.00
12.0-12.9	0	0.00
13.0-13.9	0	0.00
14.0-14.9	0	0.00
15.0-15.9	0	0.00
16.0-16.9	0	0.00
17.0-17.9	0	0.00
18.0-18.9	0	0.00
19.0-19.9	0	0.00
20.0-20.9	0	0.00
≥21.0	55	3.47
Total	**1587**	**100.00**

Reebok RealFlex		
Tread Gap Width (mm)	Length (mm)	Percentage
< 1.0	0	0.00
1.0-1.9	239	10.36
2.0-2.9	829	35.93
3.0-3.9	443	19.20
4.0-4.9	448	19.42
5.0-5.9	98	4.25
6.0-6.9	131	5.68
7.0-7.9	46	1.99
8.0-8.9	53	2.30
9.0-9.9	0	0.00
10.0-10.9	20	0.87
11.0-11.9	0	0.00
12.0-12.9	0	0.00
13.0-13.9	0	0.00
14.0-14.9	0	0.00
15.0-15.9	0	0.00
16.0-16.9	0	0.00
17.0-17.9	0	0.00
18.0-18.9	0	0.00
19.0-19.9	0	0.00
20.0-20.9	0	0.00
≥21.0	0	0.00
Total	**2307**	**100.00**

Reebok Zignano		
Tread Gap Width (mm)	Length (mm)	Percentage
< 1.0	0	0.00
1.0-1.9	24	1.43
2.0-2.9	0	0.00
3.0-3.9	361	21.57
4.0-4.9	116	6.93
5.0-5.9	0	0.00
6.0-6.9	58	3.46
7.0-7.9	617	36.86
8.0-8.9	116	6.93
9.0-9.9	155	9.26
10.0-10.9	121	7.23
11.0-11.9	86	5.14
12.0-12.9	20	1.19
13.0-13.9	0	0.00
14.0-14.9	0	0.00
15.0-15.9	0	0.00
16.0-16.9	0	0.00
17.0-17.9	0	0.00
18.0-18.9	0	0.00
19.0-19.9	0	0.00
20.0-20.9	0	0.00
≥21.0	0	0.00
Total	**1674**	**100.00**

Appendix 12: Soil Sieving Pictures

Left and below: The wet sieving apparatus. A 4” x 4” piece of disposable mesh is placed in between a 3” diameter PVC pipe and connector. After the PVC is placed into an empty 1,000 mL beaker, the soil sample is poured into the top of the connector. Distilled water is then rinsed over the sample until the water runs clear. A glass rod may be used to stir the sample as water is poured over it to ensure that the sample is thoroughly rinsed.

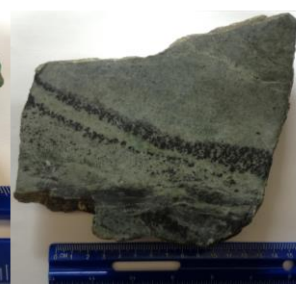
Appendix 13: L*a*b* Color Values of Geological Materials

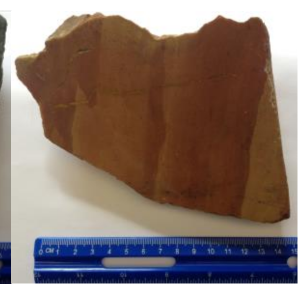
The L*a*b* color values below represent the average of 10 measurements for each sample. Compared to the soil samples in this study, both the a* and b* values tend to be lower whereas the L* values are similar. These measurements represent primary constraining values on L*a*b* values for geological materials.

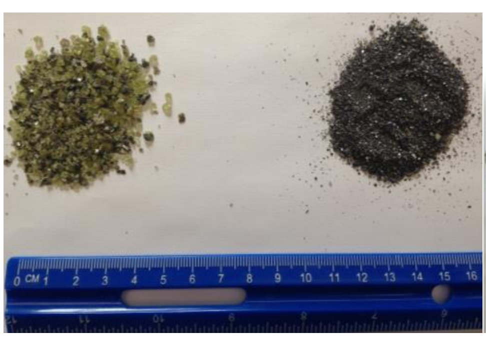
	L*	**a***	**b***
Granite	59.01	0.33	5.72
Amazonite	57.00	-12.29	4.95
Serpentine with chromite vein	52.87	-3.11	1.72
Red chert	52.16	13.32	20.68
Olivine sand	48.34	-3.77	14.19
Rodingite, Hunting Hill Quarry, Maryland	47.69	-3.27	8.03
Molybdenite	44.37	0.65	-0.74
Hematite "sand"	43.18	-5.46	-0.03
Marcellus Shale	35.11	0.47	0.73

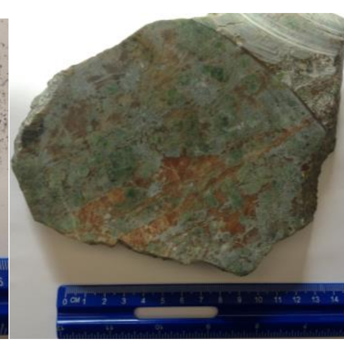

Granite


Amazonite


Serpentine with chromite vein

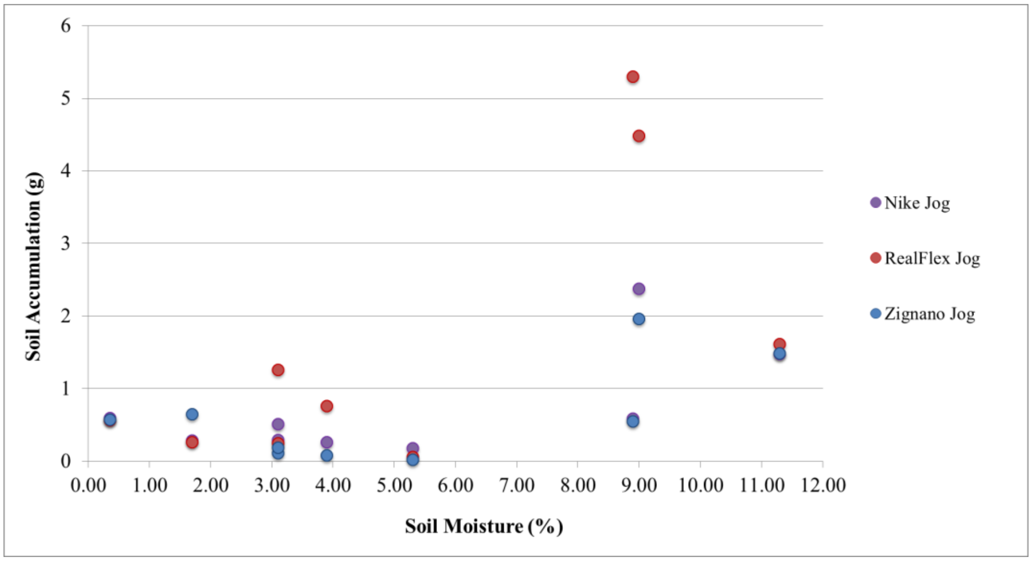

Red chert


Olivine sand (left) and hematite sand (right)

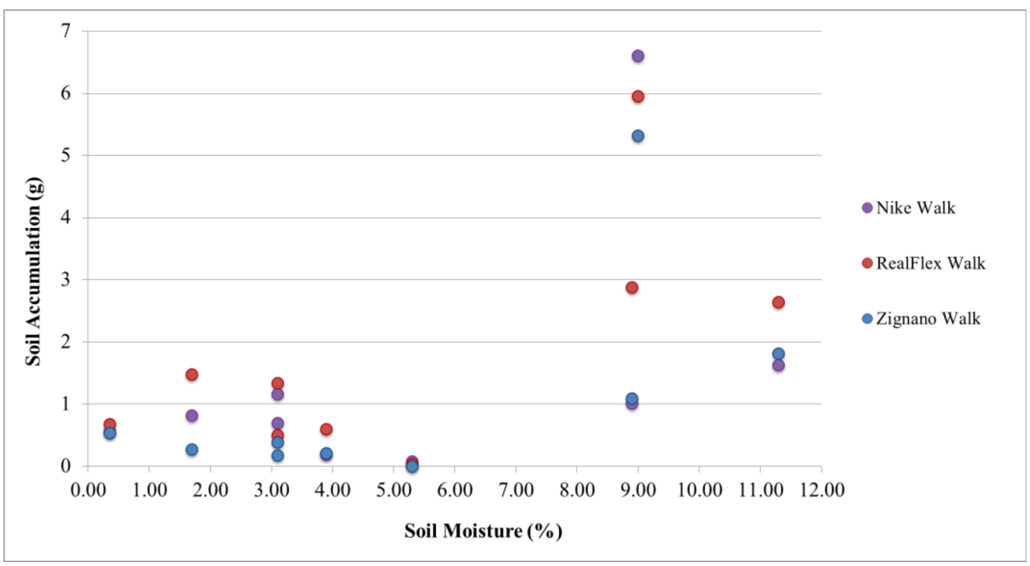

Rodingite, Hunting Hill Quarry, Maryland


Molybdenite

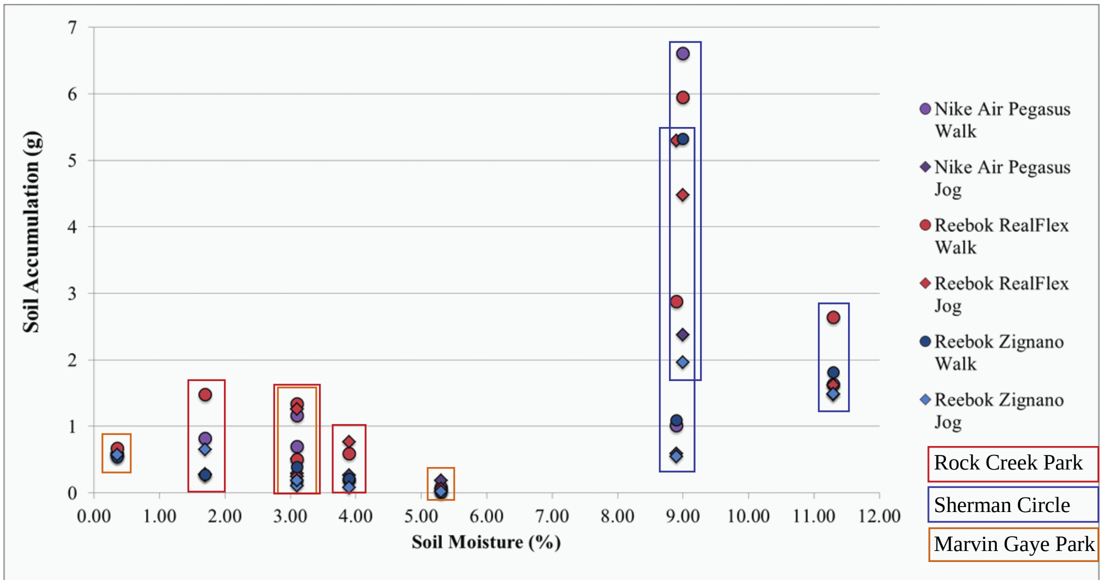
Appendix 14: Additional Soil Accumulation Plots



Soil accumulation plot with transferred soil weights for each “jog” trial.



Soil accumulation plot with transferred soil weights for each “walk” trial.



Soil accumulation plot with combined walk and jog transferred soil weights. Corresponding soil moisture contents and locations are identified with outlining boxes: red (Rock Creek Park), blue (Sherman Circle), and orange (Marvin Gaye Park).

References

Allen, B.L. and Hajek, B.F., 1989. Mineral occurrence in soil environments.. *In* J.B. Dixon and S.B. Weed (ed.) Minerals in soil environments. Soil Science Society of America Book Series No. 5. Soil Science Society of America, Madison, WI. p. 199–278.

Bottrell, M., 2011. Testimony at the Florida v. Casey Anthony trial. June 22, 2011. From Fox News Orlando, http://www.myfoxorlando.com/video?clipId=7239379. Last Accessed April 9, 2013.

Bricker, O.P., Godfrey, A.E., and Cleaves, E.T., 1968. Mineral-Water Interaction During the Chemical Weathering of Silicates. Advances in Chemistry, v. 73, Chapter 6, p. 128-142.

Bull, P.A., Parker, A., and Morgan, R. M., 2006. The forensic analysis of soils and sediment taken from the cast of a footprint, Forensic Science International, v. 162, No. 1–3, p. 6-12.

Chazottes, V., Brocard, C., and Peyrot, B., 2004. Particle size analysis of soils under simulated scene of crime conditions: the interest of multivariate analyses, Forensic Science International, v. 140, No. 2–3, p. 159-166.

Cleaves, E.T., Fisher, D.W., and Bricker, O.P., 1974. Chemical Weathering of Serpentinite in the Eastern Piedmont of Maryland. Geological Society of America Bulletin v. 85, No. 3, p. 437-444.

Croft, D.J. and Pye, K., 2004a. Multi-technique comparison of source and primary transfer soil samples: an experimental investigation, Science & Justice, v. 44, p. 21-28.

Croft, D. J. and Pye, K., 2004b. Colour theory and the evaluation of an instrumental methods of measurement using geological samples for forensic applications, Forensic Geoscience: Principles, Techniques, and Applications, Geological Society, London, Special Publications, v. 232, p. 49-62.

Dawson, L.A. and Hillier, S., 2010. Measurement of soil characteristics for forensic applications, Surface and Interface Analysis, v. 42, No. 5, p. 363-377.

DC Water Resources Research Center, 1992. Background Study of the Groundwater in the District of Columbia, report No. 103. http://www.udc.edu/docs/dc_water_resources/technical_reports/report_n_103.pdf. Last Accessed April 9, 2013.

Dixon, J.B. and Weed, S.B., 1989. Minerals in soil environments. Soil Science Society of America Book Series No. 5. Soil Science Society of America, Madison, WI.

Doner, H.E. and Lynn, W.C., 1989. Carbonate, halide, sulfate, sulfide minerals, in Dixon, J.B., and Weed, S.B., eds., Minerals in soil environments: Madison, WI. Soil Science Society of America Book Series No.5. p. 279-330.

Ducloux, J., Meunier, A., and Velde, B., 1976. Smectite, chlorite, and a regular interlayered chlorite-vermiculite in soils developed on a small serpentinite body – Massif Central, France. Clay Mineralogy, v.11, p.121-135.

Dudley, R.J., 1975. The Use of Colour in the Discrimination Between Soils, *In* Journal of the Forensic Science Society, v. 15, No. 3, p. 209-218.

Emmerich, K., Madsen, F.T., and Kahr, G., 1999. Dehydroxylation Behavior of Heat-Treated and Steam-Treated Homoionic CIS-Vacant Montmorillonites. Clays and Clay Minerals v.47, No. 5, p.591-604.

Fitzpatrick, R.W., 2009. Soil: Forensic Analysis. *In* Wiley Encyclopedia of Forensic Science, eds. A. Jamieson and A. Moenssens. John Wiley & Sons, Ltd. The Atrium, Southern Gate, Chichester, West Sussex, PO19 8SQ, United Kingdom. p. 2377-2388. http://mrw.interscience.wiey.com/emrw/9780470061589/home/.

Fitzpatrick, R.W. ad Raven, M.D., 2012. How Pedology and Mineralogy Helped Solve a Double Murder Case: Using Forensics to Inspire Future Generations of Soil Scientists. *In* Soil Horizons, v.53 No. 5.

Fitzpatrick, R.W., Raven, M.D., and Forrester, S., 2008. A Criminal Case Study Involving Transference of Acid Sulfate Soils from a Crime Scene to Forensic Evidence: Inland Acid Sulfate Soil Systems Across Australia (eds Rob Fitzpatrick and Paul Shand), p. 151-161.

Fitzpatrick, R.W., Raven, M. D., and Forrester, S. T., 2009, A Systematic Approach to Soil Forensics: Criminal Case Studies Involving Transference from Crime Scene to Forensic Evidence, Criminal and Environmental Soil Forensics, Ritz, K., Dawson, L., and Miller, D., eds., Springer Netherlands, p. 105-127.

Fleming, A.H., Drake, A.A., and McCartan, L., 1994. Geologic map of the Washington West quadrangle, District of Columbia, Montgomery and Prince Georges Counties, Maryland, and Arlington and Fairfax Counties, Virginia: United States Geological Survey Geological Quadrangle Map GQ-1748, scale 1:24,000.

Folkoff, M.E. and Meentemeyer, V., 1985. Climatic control of the assemblages of secondary clay minerals in the A-horizon of United States soils. Earth Surface Processes Landforms, v.10, No.6, p. 621–633.

Groot, J.J. and Glass, H.D., 1960. Some Aspects of the Mineralogy of the Northern Atlantic Coastal Plain. Clays and Clay Minerals, v. 7 p. 271-284.

Guedes, A., Ribeiro, H., Valentim, B., and Noronha, F., 2009. Quantitative colour analysis of beach and dine sediments for forensic applications: A Portuguese example, Forensic Science International v.190, p. 42-51.

Guthrie, R.L. and Witty, J.E., 1982. New Designations for Soil Horizons and Layers and the New Soil Survey Manual, Soil Science Society of America Journal v. 46, No. 2, p. 443-444.

Jackson, M.L. 1964. Chemical composition of soils. In F.E. Bear eds., Chemistry of the soil. p. 71-141. Reinhold Publ., New York, NY.

Jenny, H., 1941. Factors of soil formation: a system of quantitative pedology. McGraw-Hill Publishing, New York; London.

Johnson, R.R. and Kurby, P.J., 2010. STAT: University of Maryland. Cengage Learning Publishing, Mason, Ohio.

Junger, E.P., 1996. Assessing the Unique Characteristics of Close-Proximity Soil Samples: Just How Useful Is Soil Evidence?, Journal of Forensic Sciences, v.41, p. 27-34.

Kittrick, J. A., 1973. Mica-derived vermiculites as unstable intermediates, Clays and Clay Minerals v. 21, p.479-488.

Kunk, M.J., Wintsch, R.P., Southworth, C.S., Mulvey, B.K., Naeser, C.W., and Naeser, N.D., 2004. Multiple Paleozoic metamorphic histories, fabrics, and faulting in the Westmister and Potomac terrances, central Appalachian and Piedmont, northern Virginia and southern Maryland, in Southworth, S. and Burton, W., eds., Geology of the national capital region – field trip guidebook: U.S. Geological Survey Circular 1264, p. 163-188.

Locke, G., and Bertine, K.K., 1986. Magnetite in sediments as an indicator of coal combustion. *In* Applied Geochemistry, v.1, No.3, p.345-356.

Metropolitan Police Department of the District of Columbia. Annual Crime Totals by District, 2001-2011. Retrieved March 20, 2013. http://mpdc.dc.gov/page/annual-crime-totals-district-2001-2011.

Metropolitan Washington Air Quality Committee, 2002. Appendix B: Base Year 2002 Emissions Inventory and Documentation. Retrieved June 4, 2013. www.regulations.gov/contentStreamer?objectId...disposition...pdf.

Meunier, A. and Velde, B., 2004. Illite: Origins, Evolution, and Metamorphism. Springer Publishing.

Ming, D.W. and Mumpton, F.A., 1989. Zeolites in Soil. Minerals in Soil Environments, 2nd ed., eds J. B. Dixon and S. B. Weed, p. 873. Soil Science Society of America, Madison, WI.

Moody, J.B.,1976. Serpentinization: a review. *In* Lithos v.9, No.2, p.125-138.

Morgan, R.M. and Bull, P. A., 2007a. The use of grain size distribution analysis of sediments and soils in forensic enquiry, Science & Justice, v. 47, No. 3, p. 125-135.

Morgan, R.M. and Bull, P.A., 2007b. The philosophy, nature and practice of forensic sediment analysis. Progress in Physical Geography, v.31, No.1, p. 43-58.

Morgan, R.M., Freudiger-Bonzon, J., Nichols, K. H., Jellis, T., Dunkerley, S., Zelazowski, P., and Bull, P. A., 2009. The Forensic Analysis of Sediments Recovered from Footwear. Criminal and Environmental Soil Forensics, *in* Ritz, K., Dawson, L., and Miller, D., eds., Springer Netherlands, p. 253-269.

Mumpton, F.A. and C.S. Thompson., 1975. Mineralogy and origin of the Coalinga asbestos deposit. Clays and Clay Minerals, v.23, p.131-143.

Murray, R.C., 2004. Evidence from the Earth: Forensic Geology and Criminal Investigation: Missoula, Montana, Mountain Press Publishing Company.

Murray, R.C. and Solebello, L.P., 2009. Chapter 11: Forensic Examination of Soil *in* Forensic Science Handbook (2nd ed.) by Saferstein, R. Prentice Hall Publishing.

Murray, R. C. and Tedrow, J. C., 1992. Forensic geology. Prentice Hall Publishing.

Palenik, S., 2007. Heavy Minerals in Forensic Science. Developments in Sedimentology v.58, p. 937-961.

Parisio, S. 1981. The genesis and morphology of a serpentine soil in Staten Island. Staten Island Institute of Arts and Sciences, v. 31, p. 2–17.

Pope, G., Meierding, T., Paradise, T., 2002. Geomorphology’s role in the study of weathering of cultural stone. *In* Geomorphology. v.47 p. 211-225.

Pye, K., Blott, S.J., Croft, D.J., and Carter, J.F., 2006. Forensic comparison of soil samples: Assessment of small-scale variability in elemental composition, carbon and nitrogen isotope ratios, colour, and particle size distribution. Forensic Science International v. 163, p. 59-80.

Pye, K., Blott, S. J., Croft, D. J., and Witton, S. J., 2007. Discrimination between sediment and soil samples for forensic purposes using elemental data: An investigation of particle size effects. Forensic Science International, v. 167, No. 1, p. 30-42.

Rabenhorst, M.C. and J.E. Foss, 1981. Soil and geologic mapping over mafic and ultramafic parent materials in Maryland. Soil Science Society of America Journal, v. 45, p.1156-1160.

Rabenhorst, M. C., Foss, J. E., & Fanning, D. S., 1982. Genesis of Maryland soils formed from serpentinite. Soil Science Society of America Journal, v.46, No.3, p. 607-616.

Rawlins, B.G., Kemp, S. J., Hodgkinson, E. H., Riding, J. B., Vane, C. H., Poulton, C., and Freeborough, K., 2006. Potential and Pitfalls in Establishing the Provenance of Earth-Related Samples in Forensic Investigations: Journal of Forensic Sciences, v. 51, No. 4, p. 832-845.

Sawilowsky, S. S. and Blair, R.C., 1992. A more realistic look at the robustness and Type II error properties of the t test to departures from population normality. Psychological Bulletin, v. 111, No. 2, p. 352.

Schaetzl, R.J., and Anderson, S., 2005. Soils: Genesis and Geomorphology, Cambridge University Press.

Schulze, D.G., 2002. An Introduction to Soil Mineralogy. Soil Science Society of America. Soil Science Society of America Book Series No. 7 p.1-35

Schwertmann G. and Taylor R.M., 1989. Iron oxides. Minerals In Soil Environments, 2nd ed., Chap. 8, p. 379-438. Soil Science Society of America.

Simonson, R.W., 1959. Modern Concepts of Soil Genesis – A Symposium: Outline of a Generalized Theory of Soil Genesis. Soil Science Society Proceedings p. 152-155.

Sleep, N.H., Meibom, A., Fridriksson, Th., Coleman, R.G., and Bird, D.K. H2-rich fluids from serpentinization: Geochemical and biotic implications. Proceedings of the National Academy of Sciences of the United States of America, August 31, 2004, v. 101, No. 35. p. 12818–12823.

Soil Survey Division Staff. 1993. Soil Survey Manual. USDA Handbook No. 18, Issued October 1993. US GPO, Washington, DC. http://soils.usda.gov/technical/manual/contents/chapter3.html (accessed April 14, 2013).

Southworth, S. and Denenny, D., 2005. Geologic Maps of the National Parks in the National Capital Region, Washington, D.C., Maryland, Virginia, and West Virginia.USGS Open File Report 2005-1331.

Sugita, R. and Marumo, Y., 1996. Validity of color examination for forensic soil identification, Forensic Science International, v. 83, No. 3, p. 201-210.

Sugita, R. and Marumo, Y., 2001. Screening of soil evidence by a combination of simple techniques: validity of particle size distribution, Forensic Science International, v. 122, No. 2, p. 155-158.

Taupin, J.M. and Cwiklik, C., 2011. Scientific Protocols for Forensic Examination of Clothing. pp154-193. CRC Press/Taylor & Francis Group, LLC.

Tong, Jin, Ren, Luquan, Chen, Bingcong, and Qaisrani, A.R., 1994. Characteristics of Adhesion Between Soil and Solid Surfaces. Journal of Terramechanics, v.31, No. 2, p.93-105.

Rossel, V., Minasny, B., Roudier, P., and McBratney, A. B., 2006. Colour space models for soil science, Geoderma, v. 133, No. 3–4, p. 320-337.

Wanogoho, S., Gettinby, G., Caddy, B., and Robertson, J., 1989. Determination of Particle Size Distribution of Soils in Forensic Science Using Classical and Modern Instrumental Methods, Journal of Forensic Sciences, v. 34, No.4, p. 823-835.

Wildman, W.E., Jackson, M.L., and Whittig, L.D., 1968. Iron-Rich Montmorillonite Formation in Soils Derived from Serpentinite. Soil Science Society of America v. 32, No. 6, pp. 787-794.

Woods Hole Research Center. Mapping and Monitoring: Impervious Surfaces. Last Accessed June 7, 2013. http://www.whrc.org/mapping/chesapeake/impervious.html.