

Contrasting Effects on Soil Age and Parent Material  
on Hydraulic Properties in Cold Desert Ecosystems  
at Craters of the Moon National Monument and  
Preserve, Idaho, USA

By

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## Abstract

Relatively little is known about the relationship between different volcanic parent material morphologies, the degree of soil development, and how these factors might control soil hydraulic behavior. Understanding soil development and hydraulic behavior help to understand how these landscapes will develop through time, and possibly give interpretations of long-term climatic effects on ecosystem development. In volcanic soils, pedogenesis is uniquely related to the morphology of the parent material. Much of the work unto now examining pedogenesis of volcanic soils has occurred in humid, tropical environments typically receiving 2000-6000 mm of annual precipitation. Studies that characterize soil development rarely take place in dryland environments (i.e. environments where mean annual precipitation is less than the potential evaporative demand), where weathering processes are slow and soil development is primarily controlled by the accumulation of eolian sediment, rather than weathering of primary minerals. This study was conducted to determine the influence of parent material morphology and soil development on soil water behavior in a dryland system. The study was conducted at Craters of the Moon National Monument and Preserve (COTM), located in southeastern Idaho, where mean annual precipitation is 390 mm. Four study sites were selected across young (~2 ka) and old (~12-14 ka) end members of a chronosequence and two morphologically different volcanic parent materials (cinder cone deposits vs. pahoehoe lava flows). We quantified a range of edaphic soil properties including the soil moisture function ( $\Theta(h)$ ) and in situ saturated hydraulic conductivity ( $K_s$ ). Preliminary field observations showed vastly different properties between age and volcanic parent material; the cinder cone sites showed large differences in landscape development, whereas the pahoehoe sites remained dominated by unweathered basalt. Results showed that the cinder cone soils had the largest change in  $K_s$  with increasing age but only subtle differences in  $\Theta(h)$ . In contrast, the pahoehoe sites showed little change in  $K_s$  with increasing age but large differences in  $\Theta(h)$ .

Table 1. Detailed soil physical properties at each site averaged along randomly oriented transects.

Parentheses indicate standard error for each measurement group. \*Soil depths for the CCy and CCo soils are from Vaughan (2008). <sup>x</sup>See Appendix B for details in calculating SOM and for potentially important limitations to this dataset.

Table 2. Representative soil hydraulic properties for each site, including residual soil water ( $\Theta_r$ ) (expressed as volumetric water content), saturated volumetric water content ( $\Theta_s$ ), air entry value ( $\alpha$ ), saturated hydraulic conductivity ( $K_s$ ), van Genuchten parameter ( $n$ ), and the correlation coefficient ( $R^2$ ) of non-linear least squares fit curve to the measured soil water retention data.

Figure 1. Location of field sites at COTM within the eastern Snake River Plain, Idaho. Points represent the approximate location of transects, where CCy is the young cinder cone (2.1 ka), CCo is the old cinder cone (12.1 ka), Py is the young pahoehoe (2.1 ka), and Po is the old pahoehoe (13.9 ka). Polygons surrounding each point represent the spatial extent of the CCy, CCo, Py and Po features on the landscape.

Figure 2. (a) Spatial distribution of canopy cover and surficial material type along randomly oriented transects at each site. Due to time limitations, we estimated vegetation cover at only 5 locations, and then distributed the 60% vegetation across the entire transect. This is likely a conservative estimate of vegetative cover at the site. (b) Percent canopy cover or lack of vegetation summarized for the full transects. (c) Percent bare rock vs. soil cover summarized for each of the transects; subplots show percent litter-covered soil versus bare soil.

Figure 3. Representative schematic soil profiles for each site showing contrasting soil depths, horizonation, and texture between each parent material and age class. Soil horizons were classified by Vaughan (2008) for CCy and CCo, and are based on our field observations for Py and Po.

Figure 4. Average fine fraction (clay plus silt) of soil as a function of parent material and age. Letters (A, B, C) indicate statistically significant differences based on the Tukey-Kramer HSD test.

Figure 5. A representative soil water characteristic curves for each site:  $\text{Log}(\psi)$  indicates the soil water potential and  $\theta$  indicates the corresponding volumetric water content of the soil. CC values are shown in red whereas P soils are shown in black/gray. Older soils are indicated by the gray and darker maroon colors. The dashed line indicates the wilting point generally defined as 1.5MPa. Curves were fit to data collected by a WP4C dew point potentiometer (Decagon Devices, Inc., Pullman, WA).

Figure 6. Average saturated soil hydraulic conductivity ( $K_s$ ) as a function of parent material and age based on field infiltration measurements. Different letters (A, B, C) indicate statistically significant differences based on the Tukey-Kramer HSD test.

Figure 7. A conceptual model of the landscape distribution of soil hydraulic properties and vegetative cover as well as expected dominant flow paths. Arrow widths are proportional to estimated  $K_s$  values. Pahoeohoe soils develop mainly in cracks and crevices (“hot pockets”) across the landscape whereas cinder soils develop more homogeneously.

Figure 8. Modeled saturated soil hydraulic conductivity ( $K_s$ ) using Hydrus 1-D inverse modeling techniques. Modeled values are based on pedotransfer functions and are generally much lower than observed relationships. Note that vertical axis is the same as Figure 6.

Figure 9. Log-transformed soil organic matter plotted as a function of fine soil fraction. Circles represent younger parent materials, triangles represent older parent materials. Red represents cinder cone sites, and gray/black represent pahoeohoe sites. Log(SOM) increases with fine fraction for both CC and P soils, increasingly more rapidly for CC soils. For older soils of both types, there is a higher SOM content and a weaker relationship with fine fraction. See Appendix B for details in calculating SOM and for potentially important limitations of this relationship.

Figure 10. Hypothesized relationship between “ecosystem productivity” (determined by the proxy of percent cover along the transect) and time for each site. The black line indicates pahoeohoe soils whereas the red line indicates cinder cone soils. “Ecosystem productivity” is expected to increase more quickly with time in soils derived from cinder cone than pahoeohoe until a plateau is reached. This relationship is consistent the inverse texture hypothesis (Noy Meir, 1973) as well as our field observations. Cinder cone soil depths exceed those in the pahoeohoe parent material as both ages increasing potential water storage at depth. Furthermore, according to the inverse texture hypothesis, finer-textured Po soils will

have higher evaporative losses and lower productivity than coarser-textured Co soils. Coarse-textured substrate and soils will have more water available to vegetation because of increased percolation to deeper depths.

## Introduction

Plants in a dryland ecosystems use different strategies than those in humid environments to survive because the influx of water occurs episodically. The ability of soil to transport and retain water thus influences the ability of plants to thrive in water-limited systems. Noy Meir (1973) investigated the water use strategies of differently rooted plants in a semiarid environment and found a correlation between space-time stratification of soil moisture and the adaptive stratification of plant root systems. The availability of soil moisture is important in semiarid environments, where a lot of time may pass between significant infiltrations, and soil development and consequently primary succession of plants is slow and potentially punctuated by extreme droughts (Lohse et al. 1995). Understanding how soils and soil-water characteristics evolve in dryland systems and how differences in parent morphology may influence these characteristics will be important for determining resiliency of plants to more frequent droughts associated with climate change.

The development of soil is influenced by variations of climate, organisms, relief, parent material, and time (Jenny 1941). In volcanic soils, pedogenesis is uniquely related to the morphology of the parent material, which likely influences the soil's ability to support plants. Three main types of basalt morphology include a'a, pahoehoe, and cinder. Both a'a and pahoehoe basalt are a result of effusive eruptions, whereas cinder cone deposits are a result of explosive eruptions. A'a surfaces typically contain abundant crack and voids between blocks of lava, and pahoehoe is typically characterized by smooth, ropy surfaces. Cinder cone deposits contain pyroclastic rock fragments that are highly vesicular.

The weathering of basalt is rapid compared to other parent materials owing to the temperature of crystallization, and weathering increases with increasing precipitation and temperature (Navarre-Sitchler and Brantley, 2007). In Hawaii, for example, studies have shown that soil development on

basalt (as indicated by changes in mineralogy and clay content) is a function of climate (Porder et al. 2009, Chadwick et al. 2003)

The landscape at COTM creates a mosaic of spatially discontinuous volcanic surfaces that range in age (15.0-2.0 ka) and morphology (tephra, a'a', and pahoehoe). Vaughan (2008) extensively described soil development processes and textural differences, including different volcanic morphologies. She found significant differences in soil horizon development along a chronosequence of different volcanic morphologies. Furthermore, Baker et al. (2010) and Vaughan (2008) indicated that eolian sedimentation is a large component of soil development through the volcanic field, while organic inputs and in situ weathering is variable. Soil development on pahoehoe basalt is dominated by eolian sedimentation in the cracks and crevices. These eolian inputs combined with material that sometimes form organic and in situ mineral soils with desert pavements (Vaughan, 2008). Soil development and weathering processes on cinder cones includes accumulation of organic C and the weathering of rock fragments.

The objective of this study was to quantify a range of soil hydraulic properties in different soils to understand the influence of volcanic parent material morphology (with a focus on cinder cone deposits vs. pahoehoe lava flows) and the degree of soil development (2-14 thousand years of development) on soil water dynamics. Specifically, the hypotheses we considered was i) soil water holding capacity ( $\Theta$ ) will increase with surface age and ii) saturated hydraulic conductivity ( $K_s$ ) will decrease with surface age. Furthermore, we expected  $\Theta$  and  $K_s$  to be significantly different between the two volcanic substrates. This study emphasizes small-scale spatial differences in plant cover as a function of soil development, water availability, and infiltration capacity through different parent materials. We quantify  $\Theta$  and  $K_s$  data by laboratory and field methods accompanied with inverse modeling for the upper 5 cm of soil. We focused on the upper soil profile because this is a critical zone for plant-water dynamics, and may help us better understand primary succession in a dryland environment.

## Methods and Site Description

The field work for this study was conducted at Craters of the Moon National Monument and Preserve (COTM) in east central Idaho (43.46259, -113.56311). Soils on young (~2 ka) and old (~12-14 ka) end members from two morphologically different parent materials (cinder cone and pahoehoe basalt) were the focus of this study. The greater COTM area is the largest volcanic lava field in the continental USA. It covers about 1,600 km<sup>2</sup> on the eastern Snake River Plain, Idaho, and contains 30 km<sup>3</sup> of lava flows and associated vent deposits (Kuntz et al., 2007). The volcanic field is associated with the Great Rift volcanic zone. It is composed of at least 60 lava flows dating from 2.1 to 15.0 <sup>14</sup>C thousand years (ka) (Kuntz et al., 2007).

The mean annual precipitation at COTM is 390 mm with approximately 40% of the precipitation falling between April and June, and the remainder evenly distributed throughout the year. The mean annual temperature is approximately 6°C, with minimum and maximum temperatures ranging from -1 to 13°C (WRC). The topographic area has low slope relief with less than 1% except in areas with extensive deflated lava flows, where the slopes range from 0 to 60% (Vaughan, 2008). Elevation ranges from 1,500 m at the southernmost edge to 1,800 m at the northernmost edge of COTM (Figure 1). Soils at COTM are defined as Vitric Silandric Andosols on the cinder cone soils and Follic Histosols on the pahoehoe soils, both based on the World Reference Base for Soil Resources (Vaughan, 2008).

## Experimental design and measurements

We measured soil hydraulic properties in soils of different ages and volcanic morphology. The young cinder cone (CCy) and young pahoehoe were ~2.1 ka. The older cinder cone (CCo) was ~12.0 ka and the old pahoehoe (Po) was ~13.9 ka. Initial site identification was based on the geologic map of COTM (Kuntz et al., 2007). In the field, transects at random orientations were established at each the four sites. Transects at cinder cones sites were 50 meters long because we tried to stay on shallow

slopes, which were limited in length at the young site. Transects at the pahoehoe sites were 100 meters long in order to capture variability in vegetation and surficial materials. Surficial material (bare rock, bare soil, litter) and canopy (vegetation cover, no cover) was recorded every meter. In addition, depth to bedrock was recorded.

At 5 or more locations along each transect where the soil was greater than 5 cm deep, we conducted infiltration measurements (described later) and then collected these soils for determination of soil physical characteristics. Each soil sample was air-dried and coarse material (>2 mm) was sieved and weighed. Soil samples were oven dried for 12 hours at 105°C. Particle size distribution was determined using the hydrometer method (Grossman and Reinsch, 2002). Soil organic matter was determined using the loss on ignition method (Abella and Zimmer, 2007). A statistical comparison (Tukey-Kramer HSD) was used to test for significant differences in average fine material for each site.

Additional sets of soil cores were collected to determine soil bulk density. Three soil cores (4 cm diameter and 5 cm height) were carefully excavated from each cinder cone sites for bulk density. Soils were oven dried at 105 °C for 12 hours, and then bulk density was determined by dividing the oven dry soil weight by the measured cylinder volume. The excavation method (Maynard and Curran, 2007) was used to measure the bulk density from the old pahoehoe site, where it was determined by dividing the oven dry soil weight by the crevice volume occupied by soil. Crevice volume was estimated by lining the void with a thin plastic liner and filling the crevice volume with a measured volume of water. The young pahoehoe site was not measured for bulk density due to road closure and time limitations. Instead, these values were obtained from Vaughan (2008), using a same age flow. Particle density was determined using the Archimedes' liquid displacement method (Grossman and Reinsch, 2002), and porosity was calculated using

$$\Phi = 1 - (Bd/Pd)$$

where  $\Phi$  is porosity,  $Bd$  is bulk density, and  $Pd$  is particle density. Particle size was determined for only the upper 5 cm of soil at each site.

Water characteristic curves describing the relationship between the soil water potential, the tension at which water is held to the soil, and soil volumetric water content, the volume of water per volume of soil, was determined for each site. The dry end of the curve represents soil water potential measurements that were obtained for 3 samples at each site using a WP4C dew point potentiometer (Decagon Devices, Inc., Pullman, WA). First, soil samples of soil from each site were lightly packed into plastic cups provided with the potentiometer until it was approximately half filled. Each soil was saturated to its field capacity at  $\sim 0.1$  MPa. The samples were dried consecutively for 10-20 minutes at  $40^{\circ}\text{C}$ . After each drying step, decreasing soil water potential (MPa) was measured with the WP4C dew point potentiometer (Decagon Devices, Inc., Pullman, WA) until the soil was completely dry. A soil water characteristic curve was fit, using the Retention Curve (RETC) program (Van Genuchten et al., 1991), to the measured soil water potential values for each sample. The model used known soil hydraulic parameters (average field measured  $K_s$  and  $\Theta_r$ ) and predicted parameters (saturated water content, air entry value,  $n$ ) to create non-linear least squares fit curve to our measured data. Representative curves were selected for each soil based on model correlation coefficients. The saturated end of the curve was measured for the CCo site using a volumetric pressure plate (SoilMoisture Equipment Corp.) but was not completed for all sites due to time limitations.

A minidisk tension infiltrometer (Decagon Devices, Inc., Pullman, WA) was used to measure near saturated hydraulic conductivity for at least 5 locations along transects at each site where soil was greater than 5 cm deep. The minidisk infiltrometer has a 4.5 cm diameter contact surface and was set at 1 cm tension for each measurement. The soil surface was prepared by carefully removing litter and small rocks from the soil surface. Each infiltration measurement continued until steady-state infiltration

rates were reached. Average saturated hydraulic conductivity values were calculated by entering our field measured steady-state infiltration rates and field parameters (tension, soil type) into the provided macro spreadsheet (Decagon Devices, Inc., Pullman, WA). The spreadsheet estimated  $K_s$  by first determining cumulative infiltration vs. time using Zhang's equation (1997):

$$I = C_1 t + C_2 \sqrt{t}$$

where  $I$  is the cumulative infiltration (cm),  $t$  is time (seconds),  $C_1$  ( $\text{m s}^{-1}$ ) and  $C_2$  ( $\text{m s}^{-1/2}$ ) are adjustable parameters related to hydraulic conductivity ( $K$ ) and sorptivity ( $S$ ) and defined through empirical data (Philip, 1957). The hydraulic conductivity of the soil is then calculated from

$$K = C_1 / A$$

where  $C_1$  is the slope of the curve of the cumulative infiltration vs. the square root of time, and  $A$  is a value relating to van Genuchten parameters for a given soil type to the suction rate and radius of the infiltrometer disk (Decagon Devices, Inc., Pullman, WA). A statistical comparison (Tukey-Kramer HSD) was used to test for significant differences in average  $K_s$  for each site.

In addition to using Zhang's equation (1997) for obtaining  $K_s$ , and estimating water retention ( $\Theta_r$ ), a complete set of hydraulic properties were predicted through numerical inversion of the cumulative infiltration data. Inverse modeling was done with the HYDRUS 1-D program (Šimůnek et al., 2008). The program uses pedotransfer functions from an empirical dataset (Schaap and van Genuchten, 2006) that has very few soils with bulk densities that fall below  $1.0 \text{ g/cm}^3$ . To test whether this database bias influenced our modeled results, we performed a sensitivity analysis using volcanic soil bulk density properties ( $\sim 0.5 \text{ g/cm}^3$ ) and modeled  $K_s$  values. We also examined for soils with low bulk density characteristics (Schaap and van Genuchten, 2006; and personal communication (12/13)).

## **Results**

### **Flow characteristics as a function of age and volcanic morphology**

There were considerable variations in percent vegetation cover and soil development between soil ages and different volcanic morphology (Figure 2). Depth to bedrock was typically greater than 100 cm on cinder cone soils (Vaughan, 2008) and less than 25 cm on pahoehoe soils (Figure 3). The cinder cone sites had the largest change in soil development with time, whereas both pahoehoe sites remained dominated by more than 60% unweathered basalt. The CCy site had no vegetation cover, and the landscape was dominated by 100% cinder rock fragments. In contrast, the CCo site had 60% vegetation cover and soils had developed over 100% of the study transect. Soil horizons were up to 100 cm deep within the CCo site (Figure 3). CCy horizons contain cinder rock fragments that decreased in size with depth. The CCo site had A-R soil horizons with abundant gravel size cinder rock fragments in the upper horizon (Vaughan, 2008).

Soils at the pahoehoe sites were shallow (generally < 25 cm) and developed within cracks and crevices; they lacked horizon development. The Py site had 6% vegetation cover and development of 3% soil (97% basalt). Vegetation cover on the older pahoehoe site (Po) site increased to 40% vegetation cover with 41% soil of the studied transect (59% basalt). Litter cover on the soil surface increased from 39% to 83% from the Py to Po site.

### **Soil Physical Properties**

Soil particle size distributions and soil organic matter (SOM) varied with soil age and volcanic morphologies (Table 1, Figure 4). The CCy sites were dominated by coarse material and fines: silt plus clay comprised only 8% of the samples. This increased to 35% fines at the CCo site. This increase in fine material was also observed in the pahoehoe sites, although the Py had a similar texture to the CCo site. Py soils had 37% fines compared to Po with 92%. SOM also increased with time. SOM in the older cinder

cone soils (CCo) increased by 20% compared with the younger soils (CCy), and the pahoehoe soils increased SOM by 30% when comparing Py to Po. Bulk density values were generally low in all soils ( $<0.79 \text{ g/cm}^3$ ) with a small increase with parent material age (Table 1).

### **Soil-water availability as a function of soil age and volcanic morphology**

Water characteristic curves differed significantly between cinder cone and pahoehoe soils. The cinder cone soil water profiles had saturated volumetric water ( $\Theta_s$ ) content ranging from 0.4-0.6 (Figure 5, red lines). The pahoehoe soils also had a minimum  $\Theta_s$  value of about 0.4, but ranged to a maximum of 0.9 (Figure 5, black and gray lines). The lowest  $\Theta_s$  values for both sites were found at the young end of the chronosequence (CCy and Py). The young soils also had low residual water contents ( $\Theta_r$ ) relative to the older parent materials.

Within cinder cone profiles,  $\Theta_s$  for the CCy soils was lower than for the CCo soils (CCy: 0.4 vs. CCo: 0.6). The air entry value ( $\alpha$ ), the minimum suction at which air first enters the pores, was strikingly similar between the cinder cone soils (CCy:  $\sim 0.157 \text{ MPa}$  vs. CCo:  $\sim 0.254 \text{ MPa}$ ). In conjunction with these similar  $\alpha$  values, both cinder cone soils had a relatively steep desorption slope. The CCy soil had lower  $\Theta_r$  than the CCo soil (estimated at a residual soil suction of  $1.5 \text{ MPa}$ ).

Soil characteristic curves show different relationships for the pahoehoe soils. The  $\Theta_s$  for the Py soils was substantially less than for the Po soils (Py: 0.4 vs. Po: 0.9). The estimated  $\alpha$  was  $\sim 0.019 \text{ MPa}$  for the Py soils and  $\sim 0.255 \text{ MPa}$  for the Po soils. The slope of soil desorption was gentler for the Py soils than for the Po soils. Overall, the cinder cone sites show little hydrologic change over time whereas the pahoehoe soil hydrologic properties are changing much more over time.

### **Hydraulic conductivity**

Hydraulic conductivity ( $K_s$ ) decreased as the soils developed on both substrates, and differed markedly between the substrates (Figure 6). The cinder cone soils had the largest decrease in  $K_s$  (>120 cm/hr) with age, while the pahoehoe soils had approximately 30 cm/hr decrease with age. Figure 7 is a conceptual figure based on the  $K_s$  patterns and field observations that shows hypothesized infiltration patterns through each site. Infiltration experiments demonstrated a relatively vertical flow at the cinder cone sites, while excavated pedons at the pahoehoe sites revealed lateral movement of water along shallow unweathered basalt.

### **Inverse Modeling**

Our measured and modeled soil hydraulic properties differed considerably from one another (Figure 8 vs. Figure 6). In contrast to observations in cinder cone soils, the modeled results suggested that cinder cone soils retain less water with increasing soil development (increasing fine material), and  $K_s$  values increase with increasing age (Appendix C). Modeled  $K_s$  values for pahoehoe soils were reasonably close to observed  $K_s$  values. In general, modeled  $K_s$  values under field measured soil hydraulic conductivity.

### **Discussion**

Results from our study clearly show differences in the soil hydraulic behavior between four volcanically derived soils of contrasting degrees of soil development. These patterns are consistent with other studies that have examined soil development and hydraulic behavior across chronosequences of contrasting parent material (Lohse et al., 2005, Lohse et al., 1995, Kurtz et al., 2000, Kurtz et al., 2001 Meadows et al., 2008, Young et al., 2004, Vaughan, 2008).

Soil development at COTM is primarily controlled by both eolian sedimentation and in situ weathering of the basaltic parent materials (Baker et al., 2010, Vaughan, 2008, Vaughan et al., 2009, Vaughan et al., 2011). Vaughan (2008) showed that in situ weathering across cinder cone sites included

organic matter accumulation in surface horizons, desilication of primary minerals, the translocation of Fe, Al, and Ti to subsurface horizons, and accumulation of short-range order and crystalline minerals. The pahoehoe basalt weathers slowly with organic acids from lichen, moss, and vegetation (Vaughan, 2008). In situ weathering of basaltic parent material was evident through our field observations, where soil aggregates took on the morphology of pahoehoe basalt fragments and sand to gravel size rocks at the cinder cone sites. X-ray diffraction (XRD) experiments from Baker et al. (2010) indicated prominent eolian sedimentation through quartz signatures in the soils, because quartz does not occur in basalt. The addition of wind-blown quartz increases soil bulk density in the older soils. Volcanic soils typically have low bulk density values that range from 0.4 to 0.8 g/cm<sup>3</sup> (Shoji et al., 1993). We observed bulk density as low as 0.69 g/cm<sup>3</sup> on the young cindery surface within the CCy site. Cinder cone deposits have low bulk density characteristics due to the vesicular nature, while pahoehoe soils have low bulk densities due to high SOM relative to soil (Vaughan, 2008).

These changes in soil development and texture class clearly influence soil hydraulic behavior at each site (Figures 4-5). The younger soils with minimal eolian inputs and coarser texture classes have predictably lower  $\Theta_s$  values relative to the older parent material. The retention functions for the cinder cone soils generally matched expectations except they exhibited similar air entry points (i.e. tension of inflection point at top of curves; Figure 5). This similarity is also shown in similar  $\alpha$  values (Table 2), and may be explained by lower capillary rise within the CCy soil due to larger pore space, resulting in saturation at higher potentials (Dingman, 2002). Alternatively, these similarities could be a result of deficient sensitivity on the wet end from data collected using the WP4C potentiometer ( $\pm 0.5$  MPa from 0 to -5 MPa; Decagon Devices, Inc., Pullman, WA). The old and young pahoehoe curves showed large differences in  $\Theta_s$ , and intersect at lower water potentials near 10 MPa. This relationship may be explained by similar soil textural dynamics between sites where the curves converge at lower tensions, but the much higher  $\Theta_s$  at the old site is likely due to the 8.5x greater organic matter content (Table 1).

As expected,  $K_s$  declined with increasing soil development (Figure 6) for each volcanic substrate. Significantly higher CCy  $K_s$  values are likely related to the lack of fine material ( $< 10\%$ ) within the CCy soils (Figure 4). Because the CCo and Py soils have similar fine material concentrations ( $p=0.910$ ) we expected them to have similar average  $K_s$  values, but our results show that the Py had a significantly higher average  $K_s$  value than the CCo ( $p=0.013$ ) (Table 2, Figure 6). This result is likely due to the fractures in the shallow subsurface ( $< 10$  cm) basalt that directed preferential flow in the pahoehoe sites during field measurements. We also attribute the statistically indistinguishable Py and Po  $K_s$  values (Figure 6) to similar preferential flow paths in the shallow subsurface even though they had statistically different fine fraction concentrations (Figure 4).

We found that the field measured  $K_s$  values were consistent with our particle size and SOM analyses, but not the modeled  $K_s$  values. The modeled  $K_s$  values were unrealistic (Figure 8 vs Figure 6). A sensitivity analysis of the model suggested that the pedotransfer function used within the Hydrus 1-D model was not valid for soils with bulk density values less than  $1.0 \text{ g/cm}^3$  (Appendix C), like many of the soils we studied (Table 1). The use of inverse modeling to estimate soil hydraulic properties was problematic and led to impractical hydraulic conductivity estimates. The empirical database that drives the pedotransfer function lacked soils with low bulk density values, such as volcanic or glacial outwash soils. Future work on soils with low bulk densities would improve pedotransfer functions and associated predictions of their soil hydraulic behavior.

Differences in hydrological properties associated with soil development can help to explain pattern of succession in a semi-arid environment. Vegetation is established once sufficient material is accumulated within each basaltic parent material to support primary productivity. Increase plant cover accelerates eolian sediment accumulation (Vaughan, 2008) and increases organic acids that promote in situ weathering. It also acts to catch wind-blown sediment to increase accumulation in the upper soil horizons. Plant roots also propagate downward and widen cracks in pahoehoe sites (Vaughan, 2008),

promoting increased weathering and water infiltration. Rawls et al. (2003) suggest that SOM can also create a positive feedback leading to increased water adsorption and plant recruitment.

COTM provides an opportunity to study soil hydraulic behavior on a volcanic parent material in a dryland system with well constrained ages of morphologies. Soil hydraulic properties appears to be a primary control on the development of the landscape at COTM. Figure 10 shows a hypothesized relationship of parent material and ecosystem productivity through time. This figure is based on the inverse texture hypothesis (Austin et al., 2004, Noy Meir, 1973) and results found through this study (i.e. SOM increases faster within cinder cones soils). The sandy soils within young cinder cone sites may allow for increased water availability after a precipitation. Evaporative losses may be higher from the shallow and silty pahoehoe soils. Our hypothesized pattern of ecosystem productivity with age and parent material is consistent with our  $\Theta$  and  $K_s$  findings and with the inverse texture hypothesis introduced by Noy Meir (1973). Noy Meir (1973) suggested that coarse textured soil in arid and semi-arid environments increase water availability for deeply rooted plants and reduces runoff after a rainfall event. The hypothesis agrees with our observations at COTM, including the presence of deeply rooted plants (Utah junipers and limber pines) that are established throughout cinder cone sites.

The capacity of cinder cone deposits versus pahoehoe lava to capture and store water in episodic rainfall events is critical to the development of the landscape. The water holding capacity of unweathered volcanic parent materials is likely greater within cinder cone deposits due to its vesicular nature, which may be a key driving force of chemical weathering and primary productivity. The large component of eolian accumulation on soil development in this dryland system is a fundamental difference relative to humid climates. Although there are many similarities between humid and semi-arid systems, eolian sedimentation as well as precipitation and time are all important controls on the differences in soil development and ultimately on rates of ecosystem productivity.

## Conclusions

Findings from this study show large differences in soil water characteristics ( $\theta$ ) and saturated hydraulic conductivity ( $K_s$ ) between four soils of contrasting degrees of soil development, and two different volcanically derived parent materials (cinder cone deposits vs. pahoehoe lava flows), indicating that parent material morphology and time have a large effect on the soil hydrological properties. The cinder cone sites showed the largest change in  $K_s$  with small differences in  $\theta$  with age, whereas the pahoehoe sites showed little change in  $K_s$  and large differences in  $\theta$  with age. In addition, these soil hydraulic properties were vastly different for similar aged parent materials. These differences in hydraulic properties indicate that parent material morphology is a key factor to how soil formation occurs with time in a semi-arid environment, and thus how the landscape might evolve. Observations of landscape development between each parent material were drastically different. The cinder cone sites showed extensive landscape development from the young to old site, whereas the pahoehoe sites showed small changes and remained dominated by unweathered basalt. In combination, soil development and hydraulic properties observed in this study provide insights into understanding how these volcanic landscapes might respond and possibly evolve as climate patterns shift.

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| <i>Site</i> | <i>Soil Depth</i> | <i>Sand Content</i> | <i>Silt Content</i> | <i>Clay Content</i> | <i>Coarse Fraction</i> | <i>SOM<sup>*</sup></i> | <i>Bulk Density</i> | <i>Particle Density</i> | <i>Porosity</i> | <i>GPS Coordinates</i>  |
|-------------|-------------------|---------------------|---------------------|---------------------|------------------------|------------------------|---------------------|-------------------------|-----------------|-------------------------|
|             | Cm                | %                   | %                   | %                   | %                      | %                      | g/cm <sup>3</sup>   | g/cm <sup>3</sup>       |                 |                         |
| <b>CCy</b>  | 90 *              | 91.92<br>(9.0)      | 3.91<br>(8.4)       | 4.16<br>(0.9)       | 58.90<br>(4.03)        | 0.52<br>(0.34)         | 0.69<br>(0.02)      | 2.22<br>(0.16)          | 0.69            | 43.44498,<br>-113.56219 |
| <b>CCo</b>  | 117+ *            | 65.74<br>(3.7)      | 29.20<br>(3.4)      | 5.54<br>(0.5)       | 40.40<br>(3.61)        | 4.77<br>(1.15)         | 0.79<br>(0.09)      | 2.14<br>(0.03)          | 0.63            | 43.46259,<br>-113.56311 |
| <b>Py</b>   | 6.29<br>(0.754)   | 62.85<br>(3.0)      | 33.38<br>(2.7)      | 3.77<br>(0.7)       | 32.50<br>(7.87)        | 0.76<br>(0.21)         | 0.53 *<br>(0.03)    | 2.62<br>(0.03)          | 0.80            | 43.43252,<br>-113.54250 |
| <b>Po</b>   | 9.11<br>(1.27)    | 8.15<br>(1.0)       | 78.90<br>(1.0)      | 12.95<br>(0.7)      | 18.50<br>(7.97)        | 3.84<br>(0.96)         | 0.60<br>(0.05)      | 2.33<br>(0.08)          | 0.74            | 43.32118,<br>-113.81698 |

**Table 1.**

| <i>Site</i> | <i>Θ<sub>r</sub></i> | <i>Θ<sub>s</sub></i> | <i>α</i>   | <i>K<sub>s</sub></i> | <i>n</i>      | <i>R<sup>2</sup></i> |
|-------------|----------------------|----------------------|------------|----------------------|---------------|----------------------|
|             | VWC                  | VWC                  | Mpa        | cm/hr                |               |                      |
| <b>CCy</b>  | 0.0007               | 0.4267 (0.034)       | 0.0003 (0) | 128 (15.3)           | 2.127 (0.218) | 0.9809               |
| <b>CCo</b>  | 0.0157               | 0.6347 (0.087)       | 0.0003 (0) | 2.93 (1.35)          | 1.095 (0.263) | 0.9809               |
| <b>Py</b>   | 0.0142               | 0.2683 (0.037)       | 0.0007 (0) | 36.0 (13.4)          | 1.48 (0.085)  | 0.9671               |
| <b>Po</b>   | 0.0114               | 0.8962 (0.024)       | 0.0002 (0) | 16.9 (4.66)          | 2.007 (0.306) | 0.9787               |

**Table 2.**

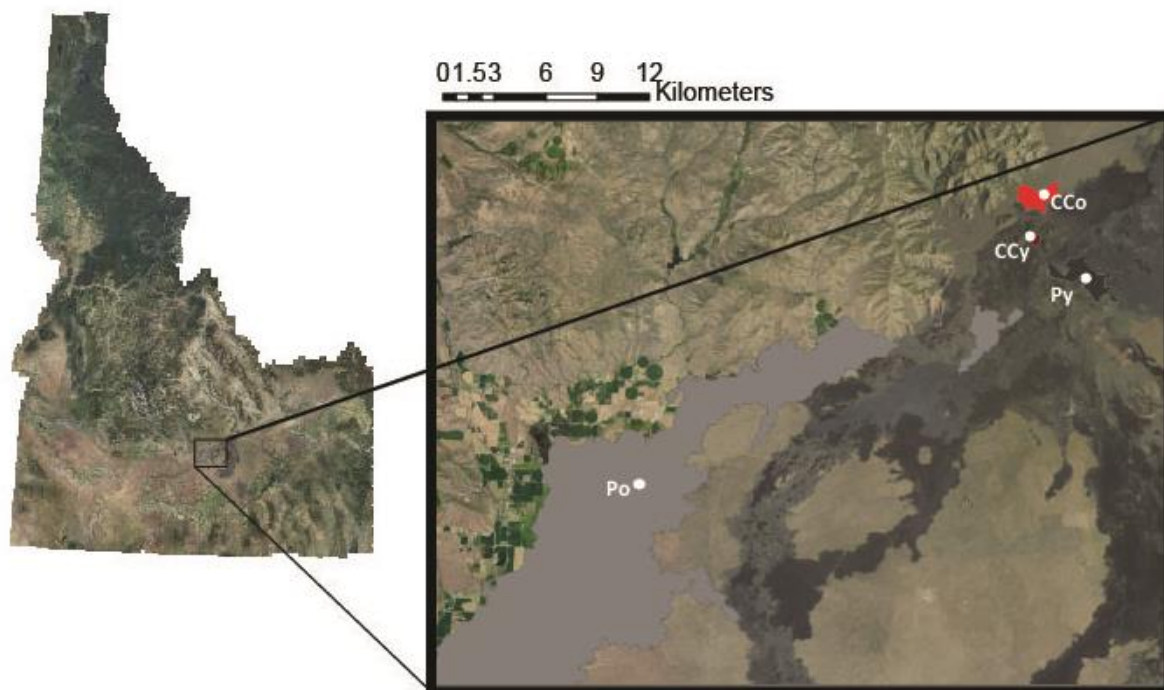


Figure 1.

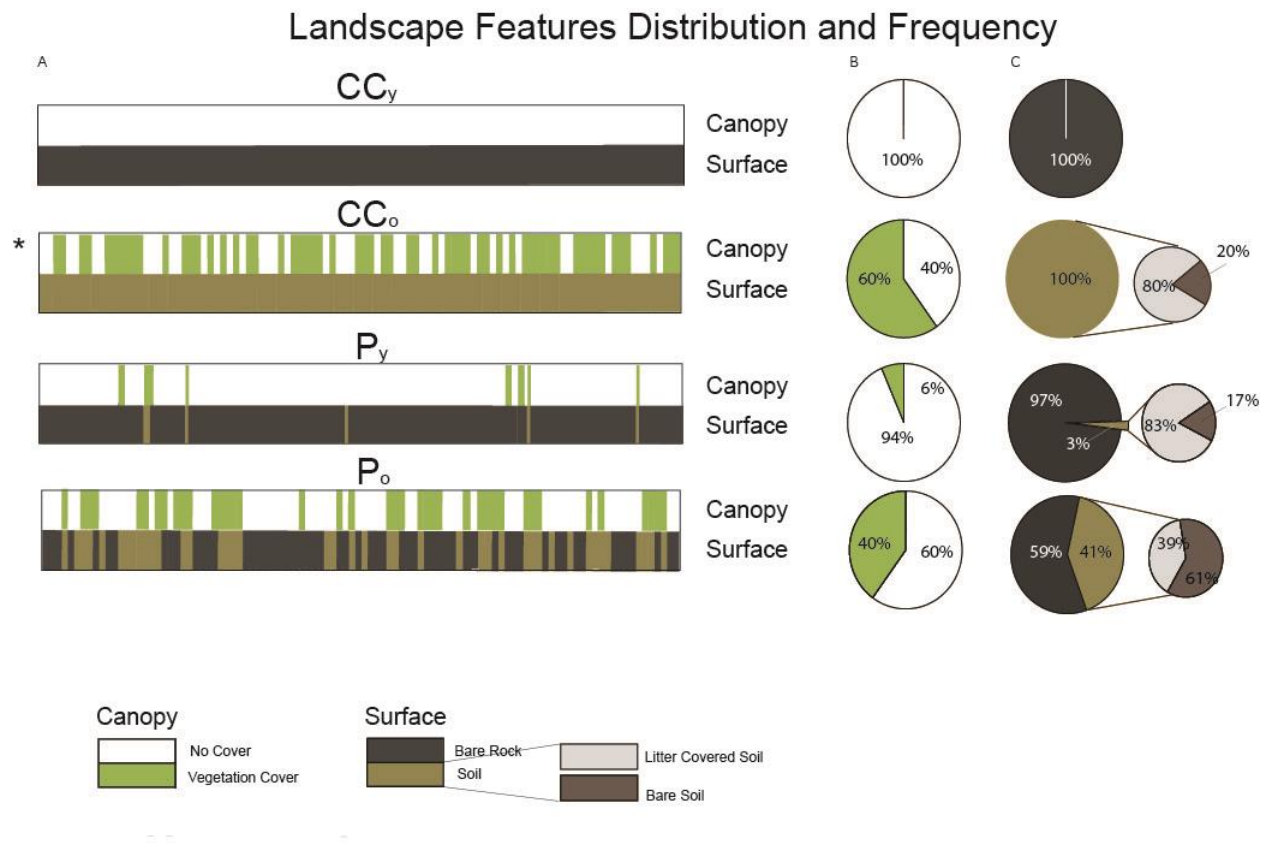


**Figure 2.**

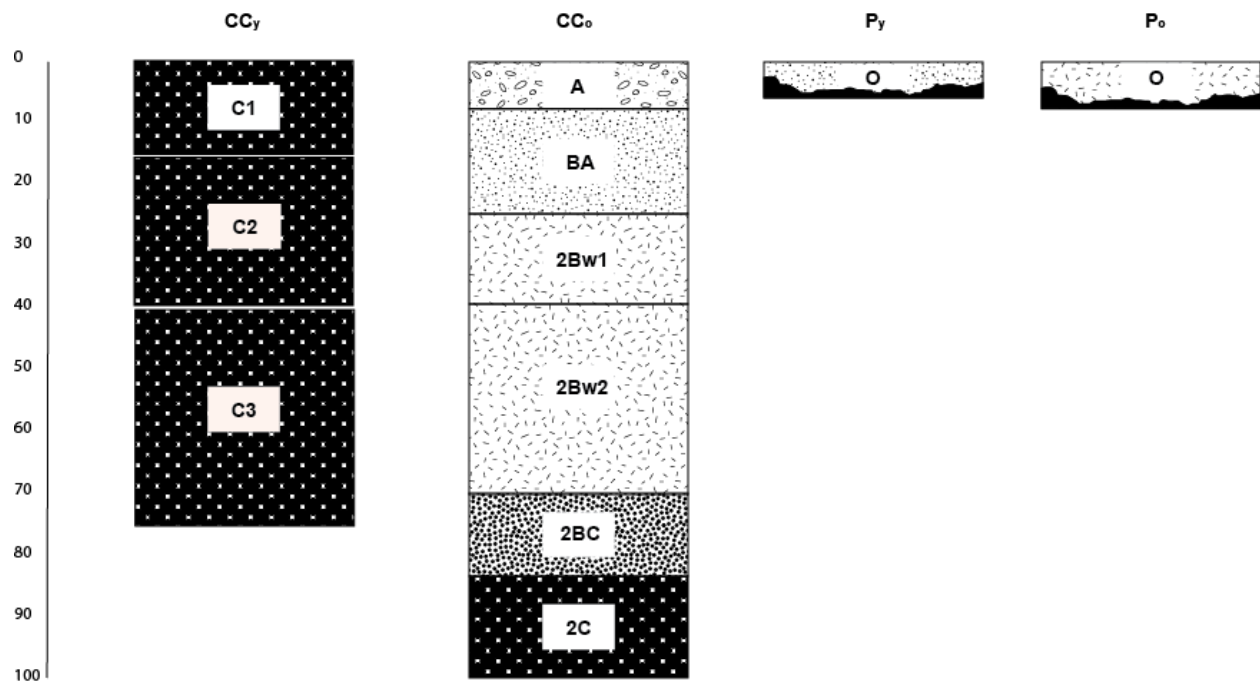


Figure 3.

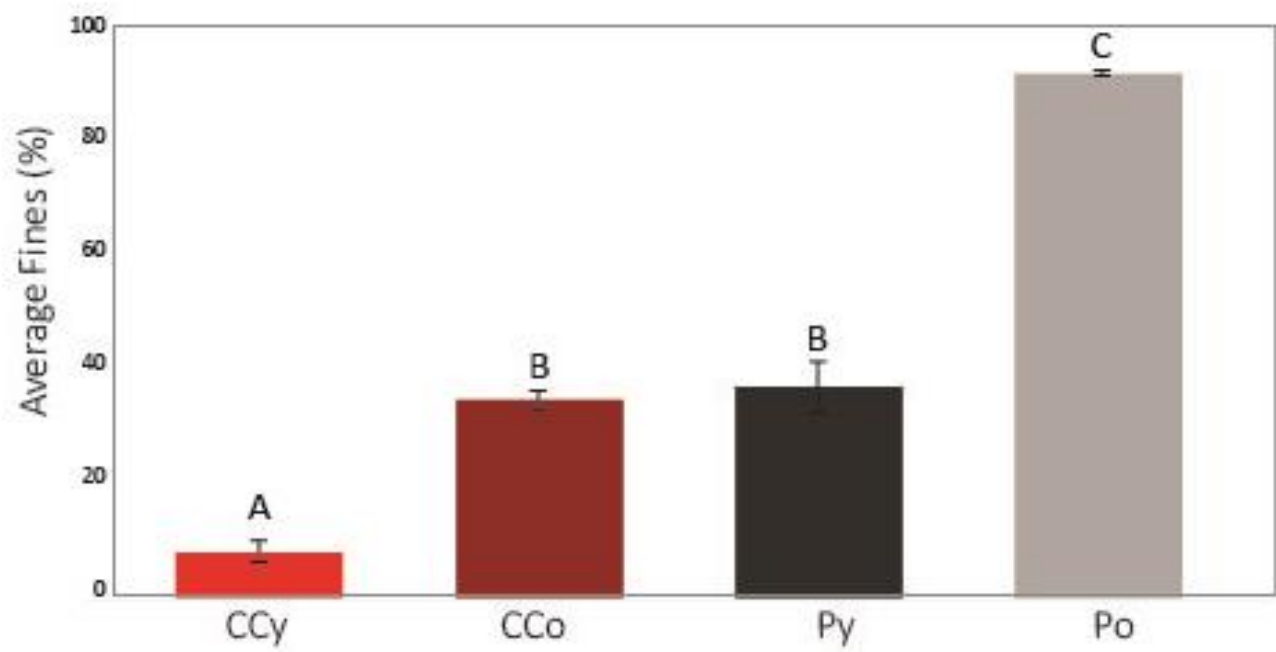


Figure 4.

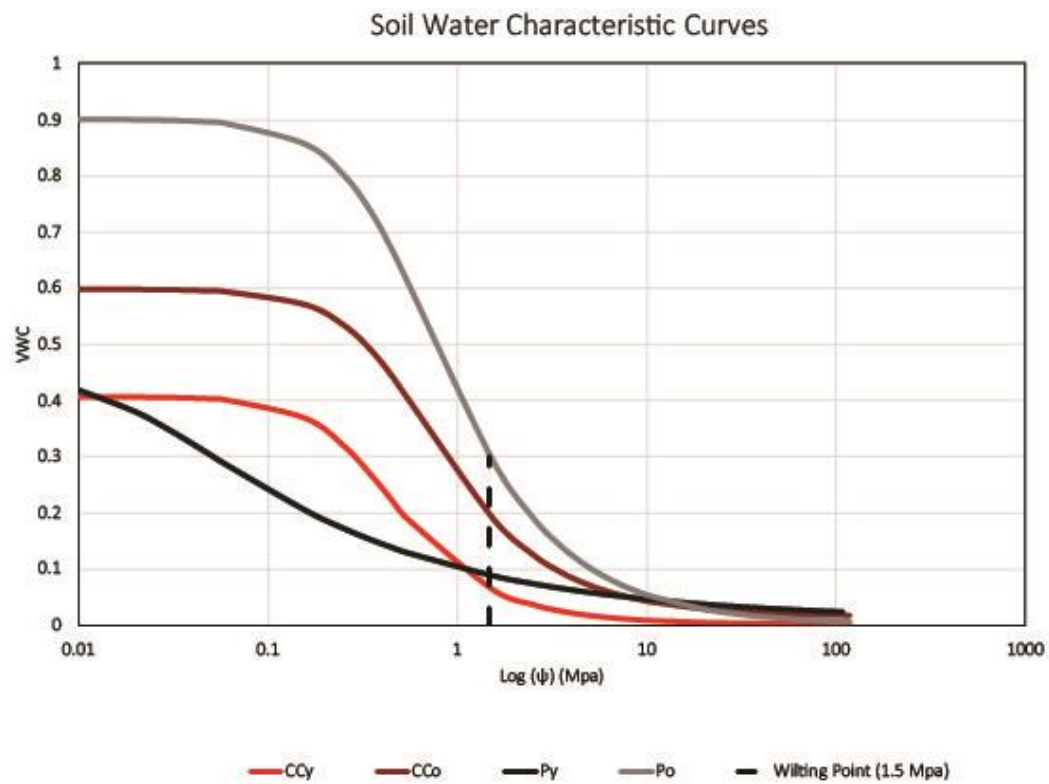


Figure 5.

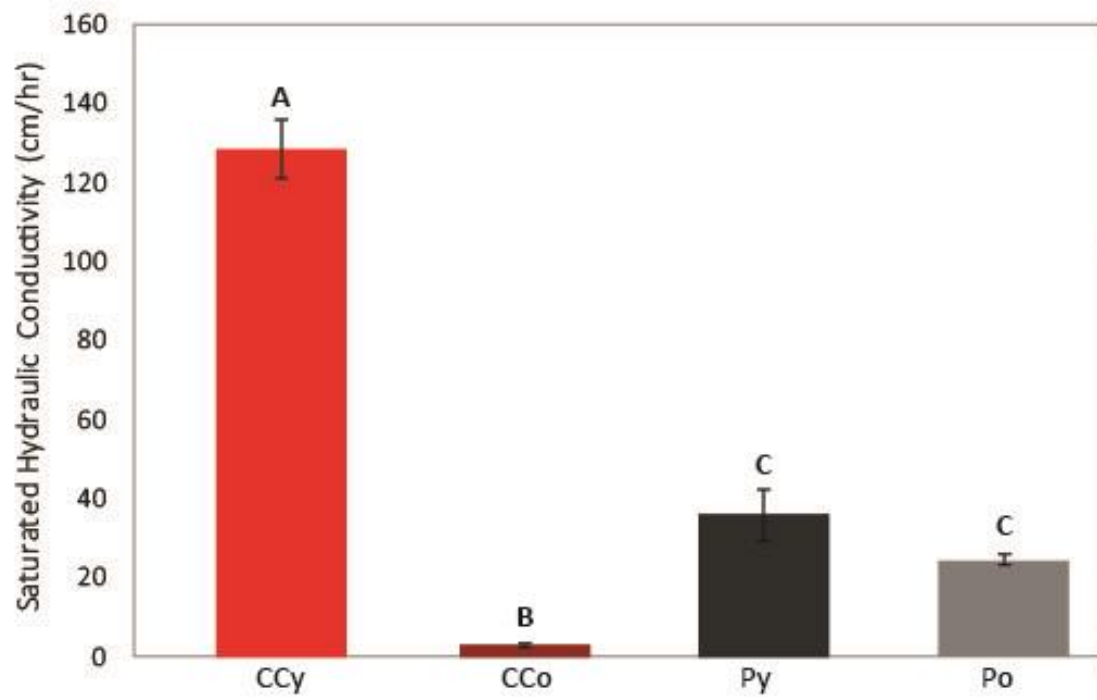


Figure 6.

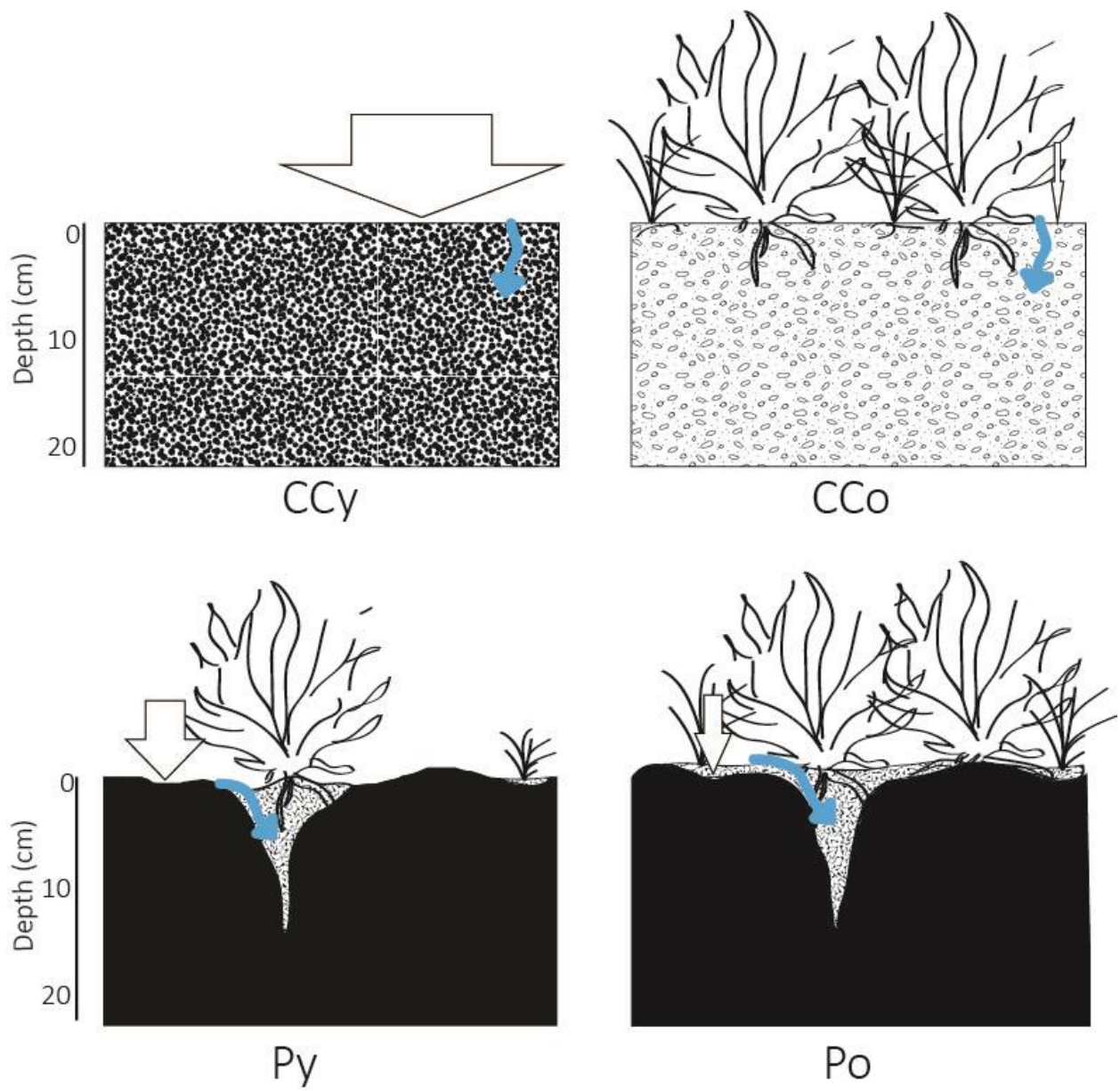


Figure 7.

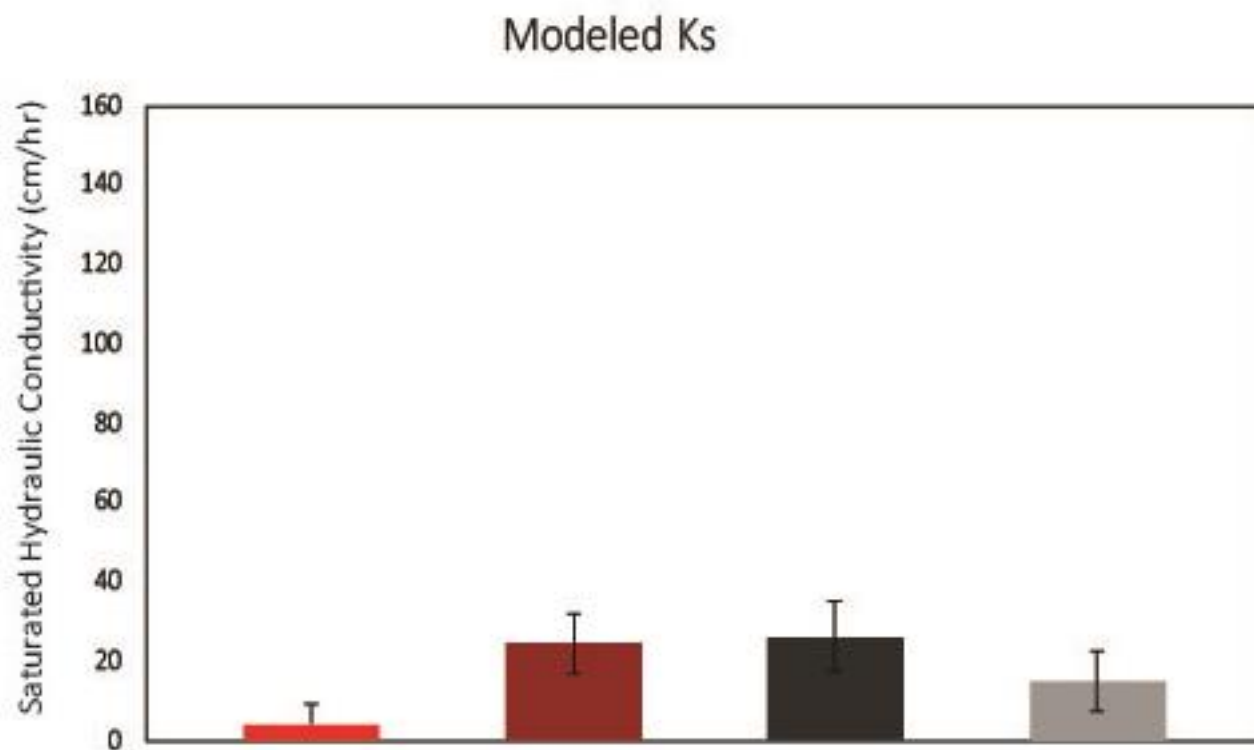


Figure 8.

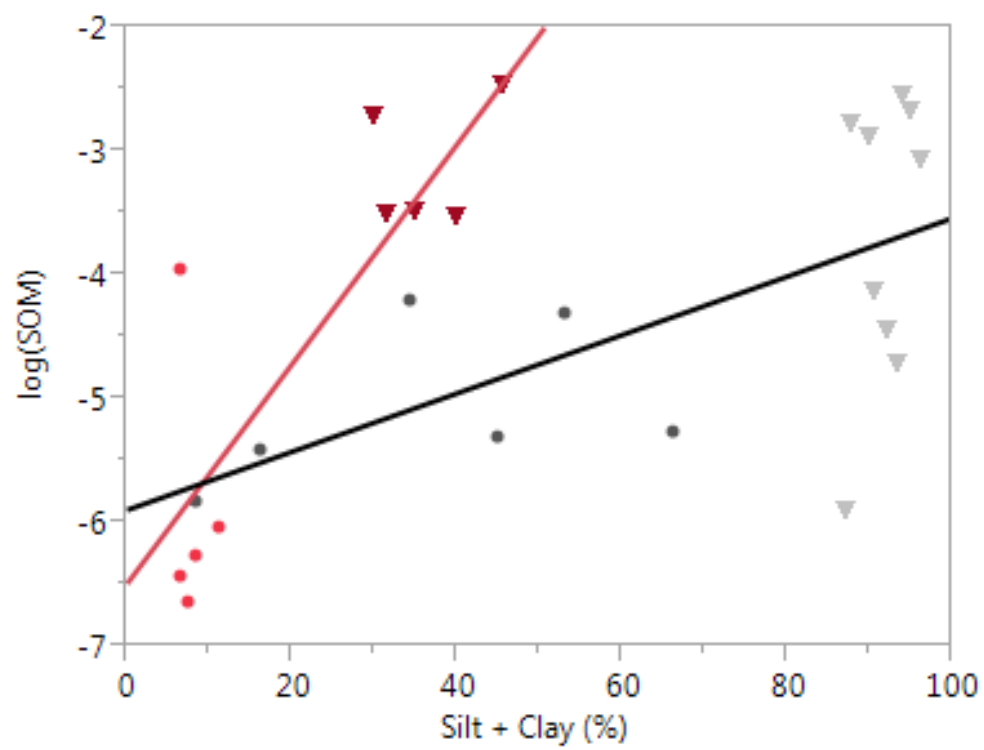


Figure 9.

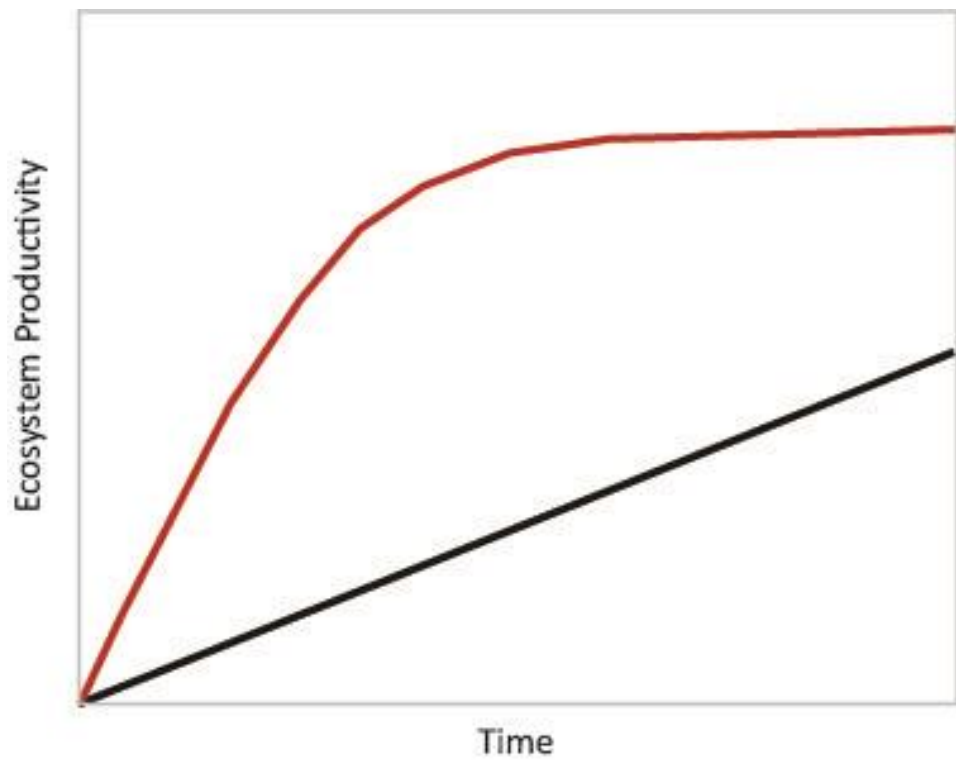


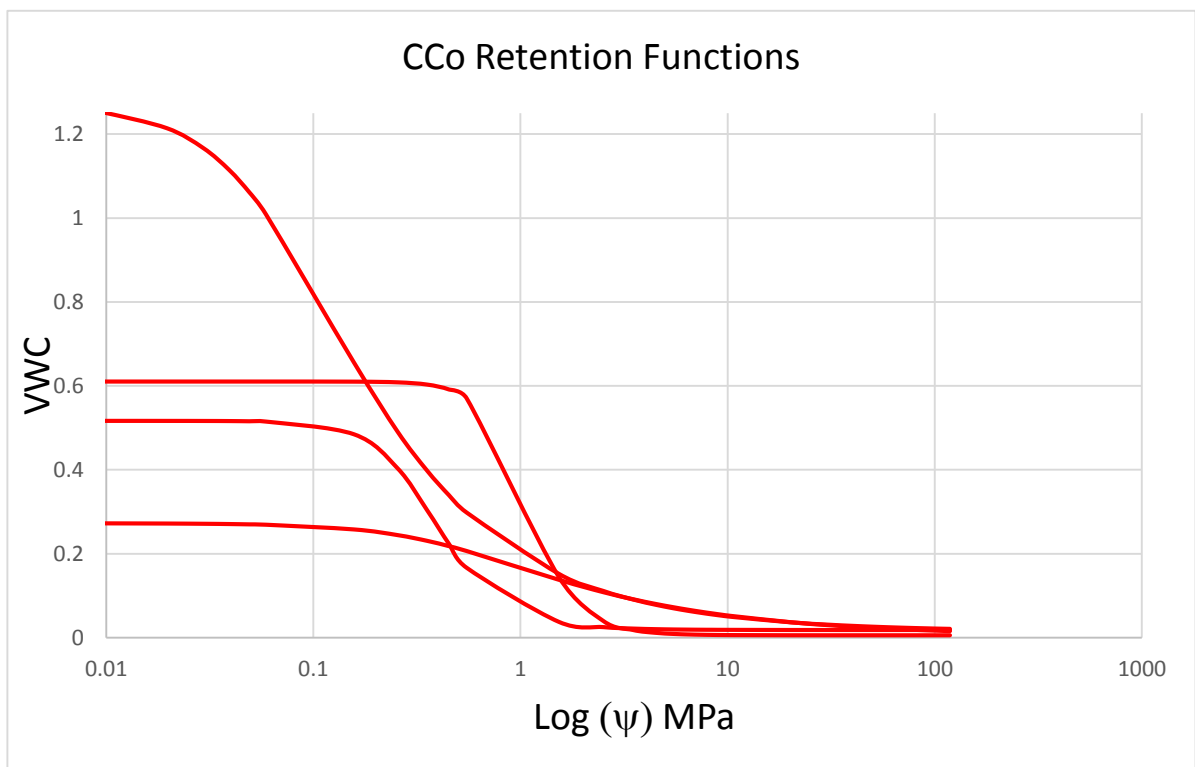
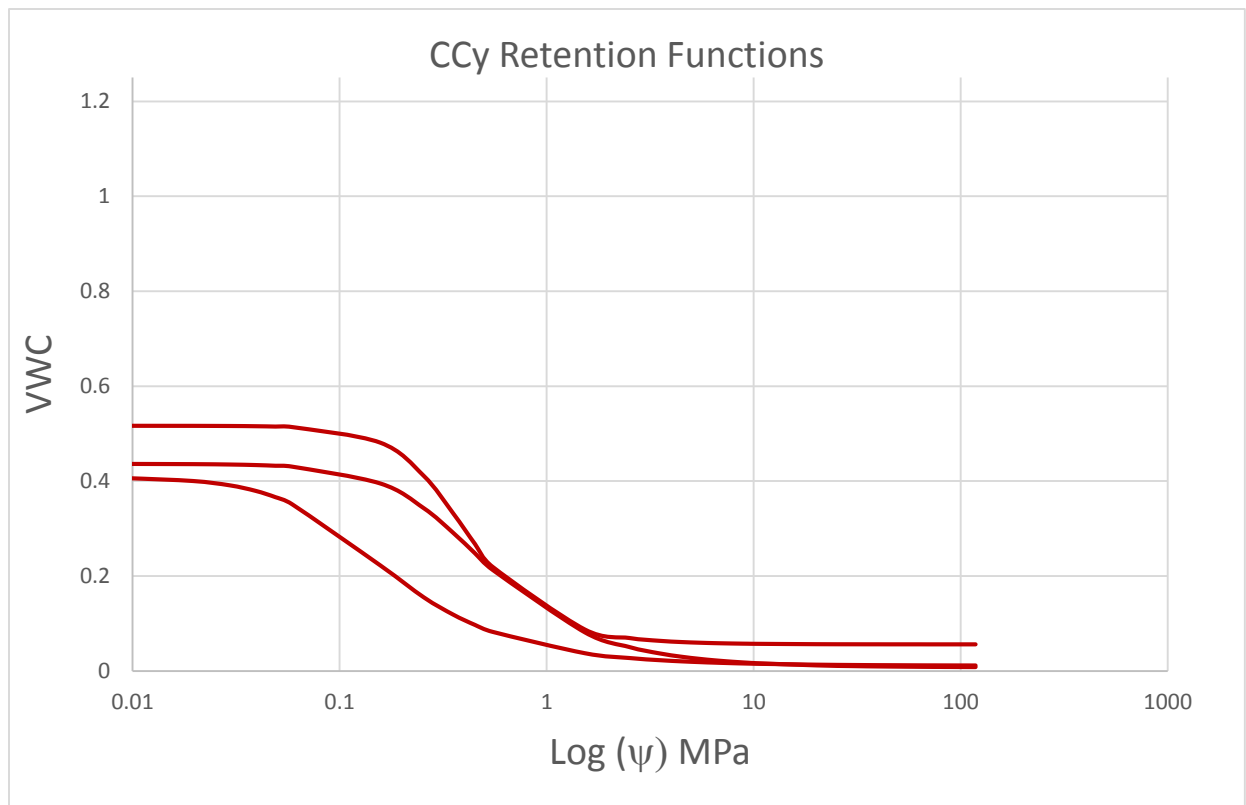
Figure 10.

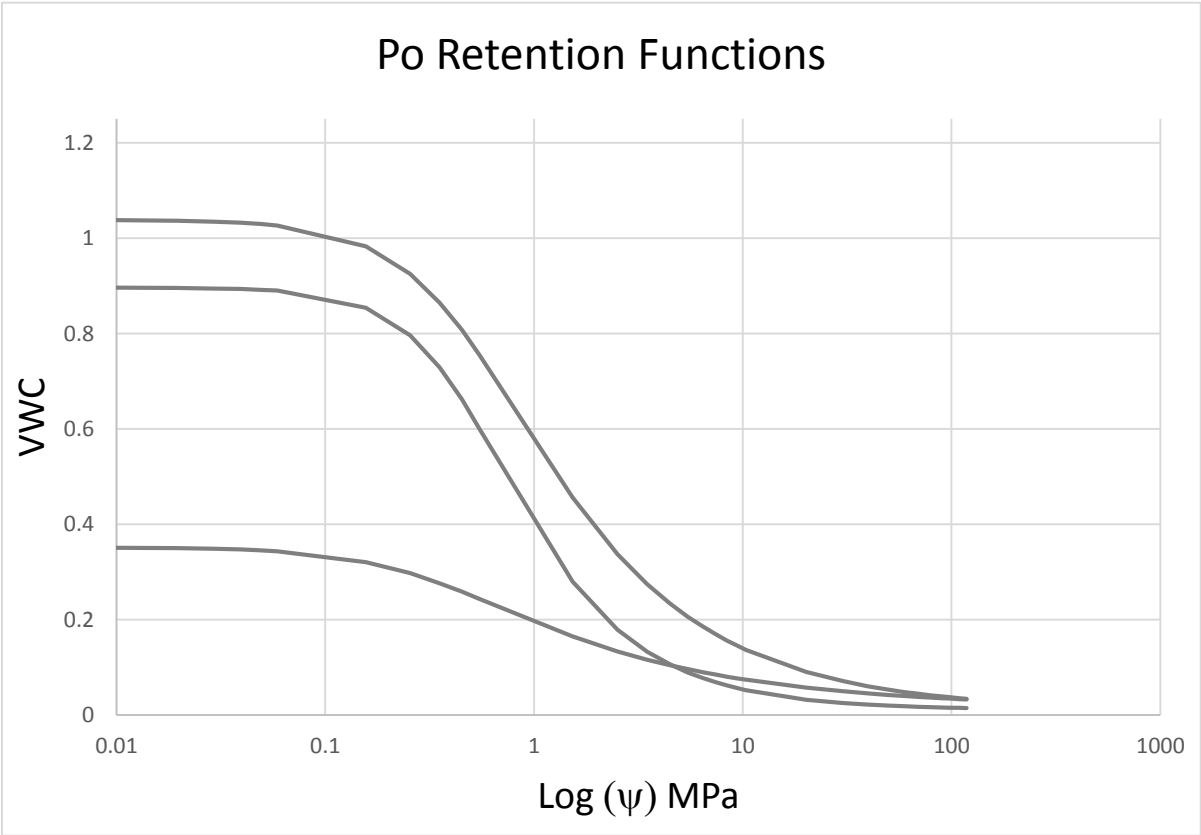
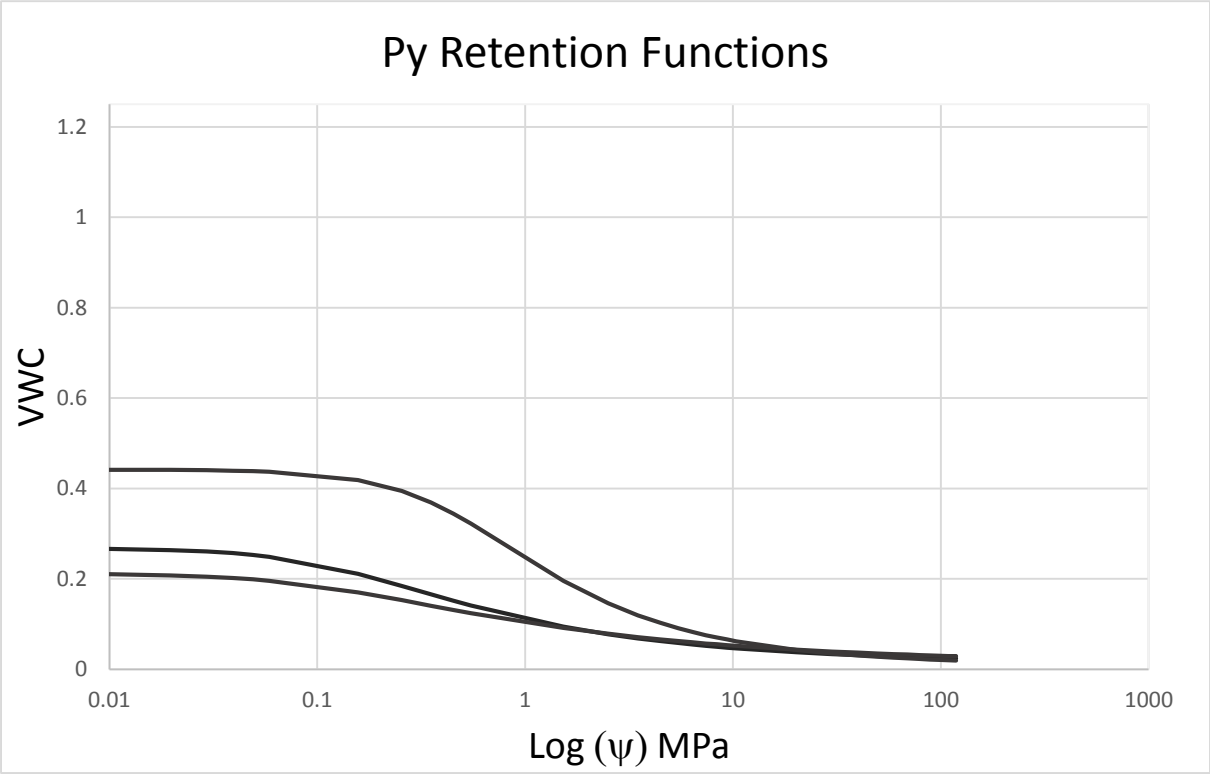
# Appendix A- Raw data (soil textures, water characteristic curves, hydraulic conductivity)

| Site | Parent Material | SOM  | Coarse Fraction | SOM  | Sand  | Silt  | Clay  | Average Sand | Average Silt | Average Clay | Average Coarse Fraction | Average SOM | Standard Error % Sand | Standard Error % Silt | Standard Error % Clay | Standard Error Coarse Fraction | Standard Error % SOM |
|------|-----------------|------|-----------------|------|-------|-------|-------|--------------|--------------|--------------|-------------------------|-------------|-----------------------|-----------------------|-----------------------|--------------------------------|----------------------|
|      |                 | g    | %               | %    | %     | %     | %     | %            | %            | %            | %                       | %           |                       |                       |                       |                                |                      |
| Ccy  | Cinder Cone     | 0.08 | 52.92           | 0.24 | 88.76 | 6.05  | 5.19  | 91.92        | 3.92         | 4.16         | 58.85                   | 0.52        | 0.87                  | 0.66                  | 0.44                  | 4.03                           | 0.34                 |
| Ccy  | Cinder Cone     | 0.07 | 50.74           | 0.19 | 91.47 | 3.87  | 4.66  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Ccy  | Cinder Cone     | 0.70 | 57.98           | 1.89 | 93.44 | 1.87  | 4.69  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Ccy  | Cinder Cone     | 0.06 | 73.81           | 0.13 | 92.60 | 4.06  | 3.33  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Ccy  | Cinder Cone     | 0.07 | 58.81           | 0.16 | 93.35 | 3.74  | 2.91  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Cco  | Cinder Cone     | 2.32 | 45.11           | 6.58 | 69.90 | 24.03 | 6.07  | 63.49        | 30.97        | 5.54         | 40.48                   | 4.77        | 2.84                  | 2.70                  | 0.59                  | 3.61                           | 1.15                 |
| Cco  | Cinder Cone     | 3.43 | 35.21           | 8.41 | 54.46 | 38.05 | 7.50  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Cco  | Cinder Cone     | 1.23 | 41.37           | 3.04 | 64.90 | 30.00 | 5.11  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Cco  | Cinder Cone     | 0.90 | 30.08           | 2.87 | 59.86 | 36.19 | 3.94  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Cco  | Cinder Cone     | 1.02 | 50.61           | 2.97 | 68.32 | 26.59 | 5.10  | 62.85        | 33.38        | 3.77         | 32.53                   | 0.76        | 9.00                  | 8.35                  | 0.94                  | 7.87                           | 0.21                 |
| Py   | Pahoehoe        | 0.70 | 21.70           | 1.48 | 65.73 | 32.77 | 1.51  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Py   | Pahoehoe        | 0.25 | 44.81           | 0.44 | 83.88 | 13.99 | 2.13  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Py   | Pahoehoe        | 0.20 | 19.51           | 0.51 | 33.87 | 61.78 | 4.35  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Py   | Pahoehoe        | 0.22 | 9.91            | 0.49 | 55.10 | 39.26 | 5.64  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Py   | Pahoehoe        | 0.11 | 62.39           | 0.29 | 91.58 | 6.56  | 1.86  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Py   | Pahoehoe        | 0.51 | 36.85           | 1.33 | 46.96 | 45.93 | 7.11  |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 1.99 | 11.03           | 6.74 | 4.94  | 82.36 | 12.70 | 8.15         | 78.90        | 12.95        | 18.57                   | 3.84        | 1.06                  | 1.10                  | 0.70                  | 7.97                           | 0.96                 |
| Po   | Pahoehoe        | 1.47 | 5.24            | 4.55 | 3.79  | 80.97 | 15.24 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 0.35 | 25.23           | 1.15 | 7.90  | 78.15 | 13.95 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 0.31 | 5.47            | 0.89 | 6.49  | 79.90 | 13.61 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 0.40 | 0.40            | 1.58 | 9.42  | 75.75 | 14.83 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 1.72 | 38.82           | 6.18 | 12.18 | 72.94 | 14.88 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 2.15 | 4.50            | 7.71 | 5.79  | 83.72 | 10.49 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 0.86 | 72.96           | 5.51 | 10.03 | 78.46 | 11.52 |              |              |              |                         |             |                       |                       |                       |                                |                      |
| Po   | Pahoehoe        | 0.05 | 3.48            | 0.27 | 12.81 | 77.89 | 9.30  |              |              |              |                         |             |                       |                       |                       |                                |                      |

| Sample | Rep | Pressure | Gravimetric Water Content | Volumetric Water Content | Pressure Head |
|--------|-----|----------|---------------------------|--------------------------|---------------|
|        |     | Mpa      |                           |                          | cm            |
| Ccy    | 1   | 0.13     | 0.30                      | 0.43                     | 1.33E+03      |
| Ccy    | 1   | 0.32     | 0.24                      | 0.35                     | 3.26E+03      |
| Ccy    | 1   | 0.24     | 0.22                      | 0.32                     | 2.45E+03      |
| Ccy    | 1   | 0.72     | 0.13                      | 0.19                     | 7.34E+03      |
| Ccy    | 1   | 0.88     | 0.10                      | 0.14                     | 8.97E+03      |
| Ccy    | 1   | 1.32     | 0.07                      | 0.11                     | 1.35E+04      |
| Ccy    | 1   | 1.98     | 0.05                      | 0.07                     | 2.02E+04      |
| Ccy    | 1   | 41.94    | 0.01                      | 0.01                     | 4.28E+05      |
| Ccy    | 1   | 2.79     | 0.01                      | 0.02                     | 2.85E+04      |
| Ccy    | 1   | 322.19   | 0.01                      | 0.01                     | 3.29E+06      |
| Ccy    | 2   | 302.34   | 0.05                      | 0.07                     | 3.08E+06      |
| Ccy    | 2   | 0.01     | 0.08                      | 0.11                     | 1.03E+02      |
| Ccy    | 2   | 0.14     | 0.07                      | 0.11                     | 1.43E+03      |
| Ccy    | 2   | 0.51     | 0.03                      | 0.05                     | 5.20E+03      |
| Ccy    | 2   | 2.38     | 0.01                      | 0.01                     | 2.43E+04      |
| Ccy    | 2   | 224.55   | 0.00                      | 0.00                     | 2.29E+06      |
| Ccy    | 2   | 0.11     | 0.19                      | 0.28                     | 1.12E+03      |
| Ccy    | 2   | 0.18     | 0.25                      | 0.36                     | 1.84E+03      |
| Ccy    | 2   | 0.03     | 0.28                      | 0.40                     | 3.07E+02      |
| Ccy    | 3   | 243.45   | 0.00                      | 0.00                     | 2.48E+06      |
| Ccy    | 3   | 0.37     | 0.24                      | 0.34                     | 3.77E+03      |
| Ccy    | 3   | 0.04     | 0.36                      | 0.52                     | 4.09E+02      |
| Ccy    | 3   | 0.68     | 0.17                      | 0.25                     | 6.94E+03      |
| Ccy    | 3   | 0.74     | 0.15                      | 0.21                     | 7.55E+03      |
| Ccy    | 3   | 0.94     | 0.07                      | 0.11                     | 9.59E+03      |
| Ccy    | 3   | 2.01     | 0.04                      | 0.06                     | 2.05E+04      |
| Cco    | 1   | 0.01     | 0.46                      | 0.59                     | 1.03E+02      |
| Cco    | 1   | 0.72     | 0.09                      | 0.12                     | 7.34E+03      |
| Cco    | 1   | 8.06     | 0.03                      | 0.04                     | 8.22E+04      |
| Cco    | 1   | 8.23     | 0.04                      | 0.05                     | 8.39E+04      |
| Cco    | 1   | 53.77    | 0.02                      | 0.02                     | 5.48E+05      |
| Cco    | 1   | 120.56   | 0.01                      | 0.01                     | 1.23E+06      |
| Cco    | 1   | 152.18   | 0.01                      | 0.01                     | 1.55E+06      |
| Cco    | 1   | 184.38   | 0.00                      | 0.01                     | 1.88E+06      |
| Cco    | 1   | 242.22   | 0.00                      | 0.00                     | 2.47E+06      |
| Cco    | 1   | 129.75   | 0.01                      | 0.01                     | 1.32E+06      |
| Cco    | 1   | 0.32     | 0.32                      | 0.40                     | 3.26E+03      |
| Cco    | 1   | 0.21     | 0.33                      | 0.42                     | 2.14E+03      |
| Cco    | 1   | 0.02     | 0.37                      | 0.46                     | 2.05E+02      |
| Cco    | 2   | 1.16     | 0.09                      | 0.12                     | 1.18E+04      |
| Cco    | 2   | 6.04     | 0.05                      | 0.07                     | 6.16E+04      |
| Cco    | 2   | 29.53    | 0.03                      | 0.04                     | 3.01E+05      |
| Cco    | 2   | 144.35   | 0.01                      | 0.01                     | 1.47E+06      |
| Cco    | 2   | 234.65   | 0.01                      | 0.01                     | 2.39E+06      |
| Cco    | 2   | 0.48     | 0.42                      | 0.54                     | 4.90E+03      |
| Cco    | 2   | 0.51     | 0.36                      | 0.45                     | 5.20E+03      |
| Cco    | 2   | 0.50     | 0.44                      | 0.55                     | 5.10E+03      |
| Cco    | 2   | 0.36     | 0.50                      | 0.63                     | 3.67E+03      |
| Cco    | 2   | 0.10     | 0.44                      | 0.56                     | 1.02E+03      |
| Cco    | 3   | 0.07     | 0.22                      | 0.28                     | 7.15E+02      |
| Cco    | 3   | 2.10     | 0.12                      | 0.15                     | 2.14E+04      |
| Cco    | 3   | 1.69     | 0.09                      | 0.12                     | 1.72E+04      |
| Cco    | 3   | 4.88     | 0.06                      | 0.07                     | 4.98E+04      |
| Cco    | 3   | 10.93    | 0.05                      | 0.07                     | 1.11E+05      |
| Cco    | 3   | 53.29    | 0.03                      | 0.04                     | 5.43E+05      |
| Cco    | 3   | 180.94   | 0.01                      | 0.01                     | 1.85E+06      |
| Cco    | 4   | 202.55   | 0.01                      | 0.01                     | 2.07E+06      |
| Cco    | 4   | 159.28   | 0.01                      | 0.02                     | 1.62E+06      |
| Cco    | 4   | 3.39     | 0.08                      | 0.10                     | 3.46E+04      |
| Cco    | 4   | 1.74     | 0.11                      | 0.14                     | 1.77E+04      |
| Cco    | 4   | 0.92     | 0.17                      | 0.21                     | 9.38E+03      |
| Cco    | 4   | 0.22     | 0.42                      | 0.54                     | 2.24E+03      |
| Cco    | 4   | 0.39     | 0.39                      | 0.50                     | 3.98E+03      |
| Cco    | 4   | 0.52     | 0.27                      | 0.34                     | 5.30E+03      |

| Sample | Rep | Pressure | Gravimetric Water Content | Volumetric Water Content | Pressure Head |
|--------|-----|----------|---------------------------|--------------------------|---------------|
|        |     | Mpa      |                           |                          | cm            |
| Py     | 1   | 0.85     | 0.06                      | 0.11                     | 8.67E+03      |
| Py     | 1   | 18.26    | 0.02                      | 0.04                     | 1.86E+05      |
| Py     | 1   | 172.53   | 0.00                      | 0.01                     | 1.76E+06      |
| Py     | 1   | 237.69   | 0.00                      | 0.00                     | 2.42E+06      |
| Py     | 1   | 1.71     | 0.05                      | 0.09                     | 1.74E+04      |
| Py     | 1   | 3.98     | 0.04                      | 0.07                     | 4.06E+04      |
| Py     | 1   | 11.76    | 0.02                      | 0.04                     | 1.20E+05      |
| Py     | 1   | 54.90    | 0.01                      | 0.02                     | 5.60E+05      |
| Py     | 1   | 9.73     | 0.03                      | 0.05                     | 9.92E+04      |
| Py     | 1   | 0.84     | 0.07                      | 0.13                     | 8.57E+03      |
| Py     | 1   | 0.21     | 0.11                      | 0.21                     | 2.14E+03      |
| Py     | 1   | 0.09     | 0.11                      | 0.22                     | 9.19E+02      |
| Py     | 2   | 0.57     | 0.06                      | 0.12                     | 5.81E+03      |
| Py     | 2   | 1.78     | 0.05                      | 0.10                     | 1.82E+04      |
| Py     | 2   | 3.69     | 0.04                      | 0.07                     | 3.76E+04      |
| Py     | 2   | 51.43    | 0.02                      | 0.03                     | 5.24E+05      |
| Py     | 2   | 160.06   | 0.02                      | 0.03                     | 1.63E+06      |
| Py     | 2   | 239.64   | 0.01                      | 0.01                     | 2.44E+06      |
| Py     | 2   | 0.01     | 0.11                      | 0.21                     | 1.03E+02      |
| Py     | 3   | 206.28   | 0.01                      | 0.01                     | 2.10E+06      |
| Py     | 3   | 0.02     | 0.47                      | 0.89                     | 2.05E+02      |
| Py     | 3   | 0.13     | 0.25                      | 0.47                     | 1.33E+03      |
| Py     | 3   | 0.25     | 0.21                      | 0.40                     | 2.55E+03      |
| Py     | 3   | 0.48     | 0.18                      | 0.34                     | 4.90E+03      |
| Py     | 3   | 0.14     | 0.16                      | 0.29                     | 1.43E+03      |
| Py     | 3   | 1.39     | 0.10                      | 0.18                     | 1.42E+04      |
| Py     | 3   | 6.24     | 0.05                      | 0.09                     | 6.36E+04      |
| Py     | 3   | 0.54     | 0.15                      | 0.29                     | 5.51E+03      |
| Py     | 3   | 0.17     | 0.25                      | 0.48                     | 1.73E+03      |
| Po     | 1   | 0.10     | 0.55                      | 0.92                     | 1.02E+03      |
| Po     | 1   | 0.52     | 0.38                      | 0.63                     | 5.30E+03      |
| Po     | 1   | 0.70     | 0.31                      | 0.52                     | 7.14E+03      |
| Po     | 1   | 1.08     | 0.25                      | 0.41                     | 1.10E+04      |
| Po     | 1   | 1.00     | 0.18                      | 0.30                     | 1.02E+04      |
| Po     | 1   | 6.41     | 0.08                      | 0.14                     | 6.54E+04      |
| Po     | 1   | 112.86   | 0.03                      | 0.05                     | 1.15E+06      |
| Po     | 2   | 0.02     | 0.68                      | 1.14                     | 2.05E+02      |
| Po     | 2   | 0.44     | 0.62                      | 1.03                     | 4.49E+03      |
| Po     | 2   | 0.67     | 0.52                      | 0.86                     | 6.83E+03      |
| Po     | 2   | 0.34     | 0.39                      | 0.65                     | 3.47E+03      |
| Po     | 2   | 0.99     | 0.35                      | 0.58                     | 1.01E+04      |
| Po     | 2   | 6.09     | 0.12                      | 0.21                     | 6.21E+04      |
| Po     | 2   | 50.87    | 0.04                      | 0.07                     | 5.19E+05      |
| Po     | 3   | 0.69     | 0.14                      | 0.23                     | 7.04E+03      |
| Po     | 3   | 34.88    | 0.04                      | 0.06                     | 3.56E+05      |
| Po     | 3   | 84.08    | 0.02                      | 0.04                     | 8.57E+05      |
| Po     | 3   | 137.89   | 0.02                      | 0.03                     | 1.41E+06      |
| Po     | 3   | 224.40   | 0.01                      | 0.02                     | 2.29E+06      |
| Po     | 3   | 235.20   | 0.01                      | 0.01                     | 2.40E+06      |
| Po     | 3   | 0.43     | 0.16                      | 0.26                     | 4.39E+03      |
| Po     | 3   | 0.11     | 0.20                      | 0.33                     | 1.12E+03      |
| Cco    | 3   | 1.69     | 0.09                      | 0.12                     | 1.72E+04      |
| Cco    | 3   | 4.88     | 0.06                      | 0.07                     | 4.98E+04      |
| Cco    | 3   | 10.93    | 0.05                      | 0.07                     | 1.11E+05      |
| Cco    | 3   | 53.29    | 0.03                      | 0.04                     | 5.43E+05      |
| Cco    | 3   | 180.94   | 0.01                      | 0.01                     | 1.85E+06      |
| Cco    | 4   | 202.55   | 0.01                      | 0.01                     | 2.07E+06      |
| Cco    | 4   | 159.28   | 0.01                      | 0.02                     | 1.62E+06      |
| Cco    | 4   | 3.39     | 0.08                      | 0.10                     | 3.46E+04      |
| Cco    | 4   | 1.74     | 0.11                      | 0.14                     | 1.77E+04      |
| Cco    | 4   | 0.92     | 0.17                      | 0.21                     | 9.38E+03      |
| Cco    | 4   | 0.22     | 0.42                      | 0.54                     | 2.24E+03      |
| Cco    | 4   | 0.39     | 0.39                      | 0.50                     | 3.98E+03      |
| Cco    | 4   | 0.52     | 0.27                      | 0.34                     | 5.30E+03      |



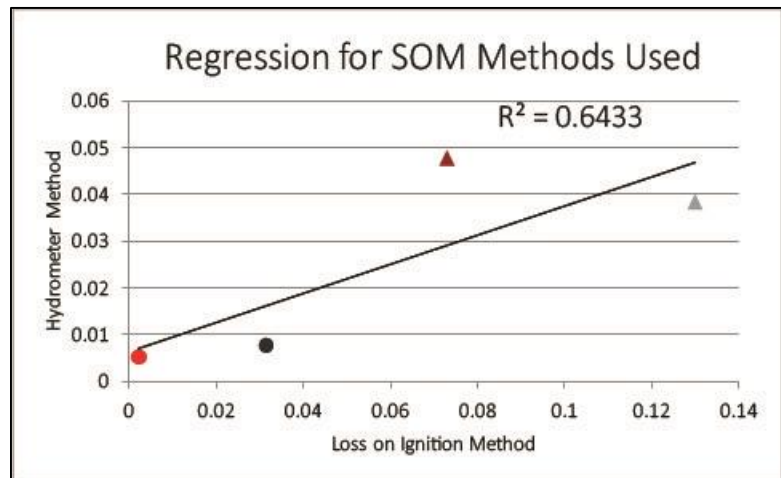


| Location on Transect | Site | Parent Material | Average Ks | Average Site Ks | Standard Error |
|----------------------|------|-----------------|------------|-----------------|----------------|
| m                    |      |                 | cm/hr      | cm/hr           |                |
| 30.00                | Ycc  | Cinder Cone     | 33.90      | 128.39          | 15.29          |
| 20.00                | Ycc  | Cinder Cone     | 91.57      |                 |                |
| 0.00                 | Ycc  | Cinder Cone     | 164.65     |                 |                |
| 40.00                | Ycc  | Cinder Cone     | 180.99     |                 |                |
| 40.00                | Ycc  | Cinder Cone     | 126.06     |                 |                |
| 40.00                | Ycc  | Cinder Cone     | 123.32     |                 |                |
| 0.00                 | Ycc  | Cinder Cone     | 117.60     |                 |                |
| 10.00                | Ycc  | Cinder Cone     | 174.22     |                 |                |
| 10.00                | Ycc  | Cinder Cone     | 143.22     |                 |                |
| 40.00                | Occ  | Cinder Cone     | 1.35       | 2.93            | 1.34           |
| 30.00                | Occ  | Cinder Cone     | 0.26       |                 |                |
| 20.00                | Occ  | Cinder Cone     | 4.84       |                 |                |
| 20.00                | Occ  | Cinder Cone     | 8.82       |                 |                |
| 50.00                | Occ  | Cinder Cone     | 1.43       |                 |                |
| 10.00                | Occ  | Cinder Cone     | 0.91       |                 |                |
| T1-53m               | Yp   | Pahoehoe        | 0.26       | 35.99           | 13.36          |
| T2-4m                | Yp   | Pahoehoe        | 17.36      |                 |                |
| T2-3m                | Yp   | Pahoehoe        | 45.18      |                 |                |
| T2-3m                | Yp   | Pahoehoe        | 38.05      |                 |                |
| T2-x m               | Yp   | Pahoehoe        | 79.11      |                 |                |
| T2-45m *             | Yp   | Pahoehoe        | 0.00       |                 |                |
| 17.00                | Op   | Pahoehoe        | 20.36      | 24.53           | 4.66           |
| 69.00                | Op   | Pahoehoe        | 22.73      |                 |                |
| 69.00                | Op   | Pahoehoe        | 20.49      |                 |                |
| 20.00                | Op   | Pahoehoe        | 5.90       |                 |                |
| 30.00                | Op   | Pahoehoe        | 13.38      |                 |                |
| 30.00                | Op   | Pahoehoe        | 11.12      |                 |                |
| 45.00                | Op   | Pahoehoe        | 24.53      |                 |                |
| 31.00                | Op   | Pahoehoe        | 6.09       |                 |                |
| 54.00                | Op   | Pahoehoe        | 10.75      |                 |                |
| 54.00                | Op   | Pahoehoe        | 39.19      |                 |                |
| 51.00                | Op   | Pahoehoe        | 61.13      |                 |                |
| 83.00                | Op   | Pahoehoe        | 37.95      |                 |                |
| 83.00                | Op   | Pahoehoe        | 45.32      |                 |                |

## Appendix B- Regression for SOM methods used

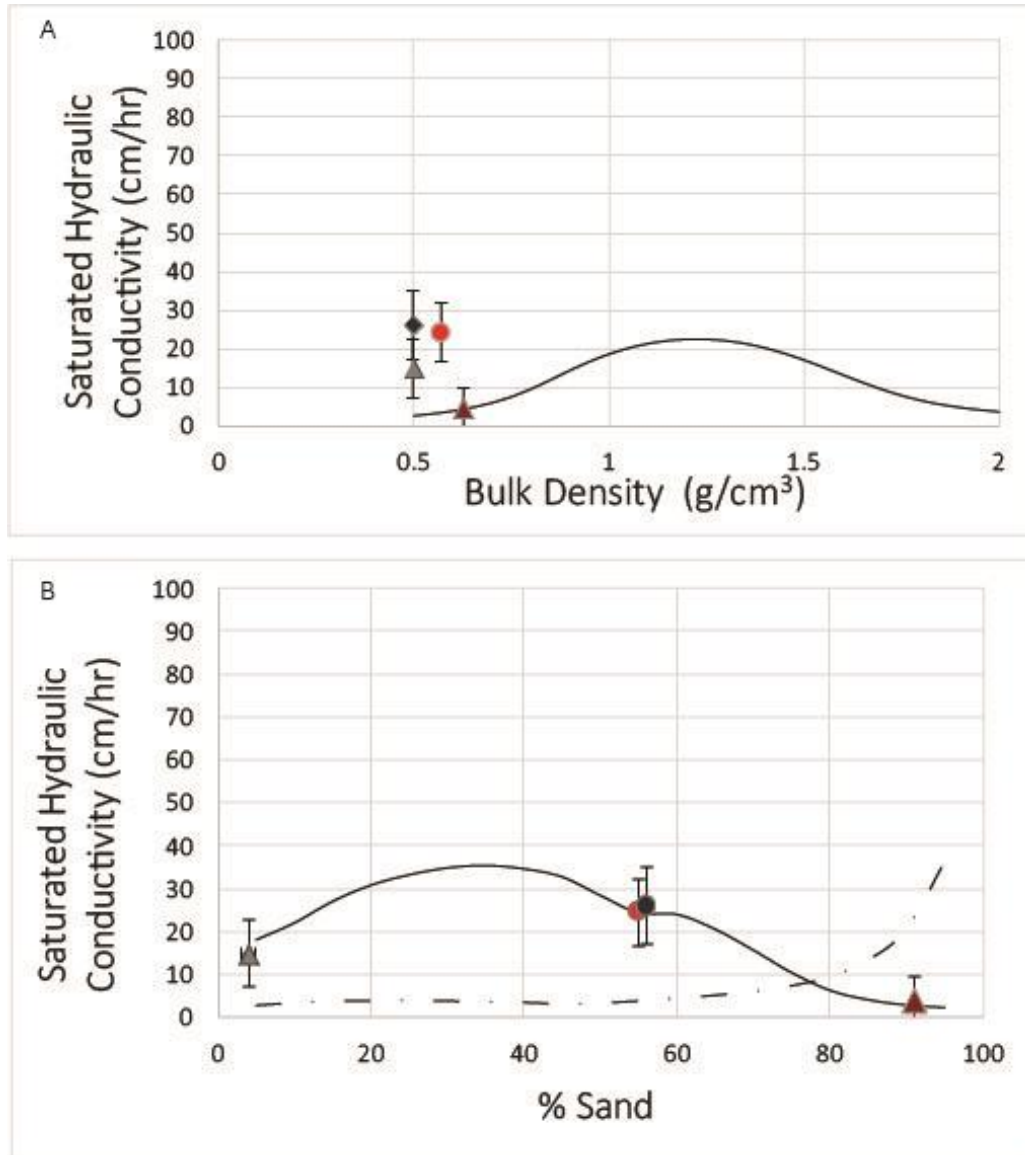
| Loss on Ignition Method |       |            |
|-------------------------|-------|------------|
| Site                    | % SOM | Avg. % SOM |
| Cco                     | 0.003 | 0.002      |
| Cco                     | 0.002 |            |
| Cco                     | 0.002 |            |
| Ccy                     | 0.100 | 0.073      |
| Ccy                     | 0.065 |            |
| Ccy                     | 0.054 |            |
| Py                      | 0.009 | 0.032      |
| Py                      | 0.063 |            |
| Py                      | 0.023 |            |
| Po                      | 0.087 | 0.130      |
| Po                      | 0.264 |            |
| Po                      | 0.039 |            |
|                         |       |            |

| Hydrometer Method |       |            |
|-------------------|-------|------------|
| Site              | % SOM | Avg. % SOM |
| Ccy               | 0.244 | 0.524      |
| Ccy               | 0.192 |            |
| Ccy               | 1.893 |            |
| Ccy               | 0.133 |            |
| Ccy               | 0.157 |            |
| Cco               | 6.576 | 4.774      |
| Cco               | 8.411 |            |
| Cco               | 3.045 |            |
| Cco               | 2.874 |            |
| Cco               | 2.967 |            |
| Py                | 1.484 | 0.758      |
| Py                | 0.441 |            |
| Py                | 0.509 |            |
| Py                | 0.494 |            |
| Py                | 0.291 |            |
| Py                | 1.326 |            |
| Po                | 6.737 | 3.841      |
| Po                | 4.548 |            |
| Po                | 1.149 |            |
| Po                | 0.890 |            |
| Po                | 1.578 |            |
| Po                | 6.180 |            |
| Po                | 7.709 |            |
| Po                | 5.506 |            |
| Po                | 0.273 |            |



Soil organic matter (SOM) reported in this study included only SOM using the hydrometer method (Grossman and Reinsch, 2002), rather than the loss on ignition method (Abella and Zimmer, 2007). Our data show an underestimation of SOM using the hydrometer method. However, the regression shown above confirms a positive association for SOM with age.

## Appendix C – Model Sensitivity analyses



## Appendix D- Field Photos



CCy



CCo



Py



Po