SOIL ORGANIC MATTER DISTRIBUTION IN A DOUGLAS-FIR-TANOAK FOREST, HUMBOLDT COUNTY, CA

By

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ABSTRACT

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Soil carbon (C) affects the active gases in the atmosphere, nutrient cycling, and diversity of flora and fauna. Soil organic matter (SOM) is partially comprised of C, and a widely-accepted ratio of 0.58 organic carbon (OC) to organic matter (OM) is used to measure soil C on a landscape scale. However, this ratio varies according to vegetation, depth, hydrology, and may lead to miscalculations of soil C and SOM estimates. Soil C and SOM are inherently complex and it is not completely understood which environmental factors have the most influence in their formation, which occurs on a time scale of decades to thousands of years. In order to accurately assess soil C and SOM on an appropriate time scale, baseline studies of inventory and investigations of relationships with environmental factors are needed.

Soils from two trenches at the L.W. Schatz Demonstration Tree Farm (LWSDTF) were sampled for SOM and SOC. The east trench was trench located at the toe slope in a position of accumulation and the west trench was located at the edge of a convex shoulder. This study investigated the amount of SOM and SOC currently present at LWSDTF using site specific OC:OM ratios, and analyzed the relationships between SOM and depth, bulk density, roots, and distance from tree bole.

I found a negative correlation of SOM with depth and bulk density, and a positive correlation between SOM and root abundance. I found large variability with SOC and SOM estimates with different sampling methods, and it is possible that the variability in SOM attributed to land use is smaller than the variability in SOM attributable to bulk density measurements. Soil organic matter increased with distance from tree bole, but this relationship is confounded by a forested setting and is not thought to accurately reflect ecological processes. The baseline inventory of SOM was 670 Mg OM ha^{-1} from east trench data and 490 Mg OM ha^{-1} from west trench data. The baseline inventory of SOC was 322 Mg C ha^{-1} from east trench data, and 200 Mg C ha^{-1} from west trench data using site specific ratios. These numbers represent a large potential C storage at the LWSDTF, and these findings may be used in future studies to inform future land management decisions.

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INTRODUCTION

According to the International Panel on Climate Change, there are five terrestrial carbon pools: aboveground biomass, belowground biomass, litter, woody debris, and soil organic matter (SOM) (Eggleston et al., 2006). The soil carbon (C) pool includes all SOM and plays a major role in the global C cycle and impacts the composition of active gases in the atmosphere, soil quality and productivity, the cycling of elements, diversity of flora and fauna, and purification of water by denaturing and filtering pollutants (Lal & Follett, 2009). The soil C pool is estimated to be about 1.5 x 10^{18} g, which is twice the amount of total C in the atmosphere (Schlesinger, 1990). Carbon dioxide (CO_2) fixed by plants during photosynthesis is transferred across C pools and underground soil processes play a key role in ecosystems' responses to atmospheric CO_2 concentrations (Iversen, 2010).

Soil C sequestration is defined as the biotic process where atmospheric CO_2 is transferred into a long-term C pool (Lal, 2004). The rate of sequestration ranges from 100 to 1000 kg ha^{-1} yr^{-1}, depending on land use, surface organic matter (OM) quality, management practices, soil properties, landscape position, and climate (Lal & Follett, 2009). Soil organic carbon (SOC) differs widely on a global scale. The soil C stock may comprise as much as 85% of the terrestrial C stock in the boreal forest, 60% in temperate forests and 50% in tropical forests (Dixon et al., 1994). Annual C sequestration of forests in the United States is estimated to vary between 149 and 330 million tons (Zhang et al., 2010).

It is important to distinguish between long-term and short-term C cycling in the soil. On a long-term scale, inorganic components of soil form carbonates through weathering, but these carbonates do not appear influential in short-term C cycling, with present sequestration estimated at only 4 x 10^{-13} g C yr^{-1} globally (Holmen, 1992). A long-term (recalcitrant) soil C pool consists of OM that is strongly stabilized on mineral surfaces and is chemically and physically protected from decomposition (the breakdown of larger organic molecules into smaller simpler parts) (Trumbore, 2000). This study focuses on short-term (active) C and organic soil components which have more sensitivity to land management than particulate organic C and microbial biomass C (Culman et al., 2012; Page-Dumroese et al., 2015).

Soil organic matter is an important resource under actively managed forests, agricultural lands, and rangelands worldwide (Torn et al., 2009). The initial source of SOM comes from CO_2 fixed from the atmosphere by plant photosynthesis. When the plant dies or sheds its leaves, needles or branches, its organic matter is added to the soil in the form of litter or dead roots (Kutsch et al., 2009). This plant detritus is comprised of organic compounds such as sugars, starches, proteins, carbohydrates, lignins, organic acids, waxes, and resins (Trumbore, 2000). Soil fauna like fungi and microbes transform chemical compounds in OM and C in the active pool by way of decomposition or oxidation into plant-accessible forms during a process called mineralization (NRCS, 2011). Organic matter is the main energy and C source for heterotrophic microorganisms. Decomposition begins with sugars and starches, while more complex molecules (cellulose, hemicellulose, and lignin) break down more slowly (Dixon et al.,

1994). The rate of decomposition varies depending on the amount and quality (i.e. C:N ratio) of SOM being decomposed (NRCS, 2009). End products of mineralization include CO_2 and plant available nutrients. Eventually humus also forms as a chemically stable organic compound made up of plant, animal, and microbial origin (Houghton, 2005). Humus is particularly important to an ecosystem due to the oxygen that it holds in larger molecular assemblages, which creates negatively charged sites that bind to plant nutrient ions, making these nutrients available to the plant though ion exchange.

Organic matter in soils is the largest C reservoir in rapid exchange with atmospheric CO_2, and is thus important as a potential source and sink of greenhouse gases over time scales of human concern (Fischlin & Gyalistras, 1997). To improve and locate natural sinks for soil C sequestration, we must understand what influences soil C in forest soils (Lal, 2005). Due to climate change, interest in sequestering atmospheric CO_2 emitted by combustion of fossil fuels has increased, and the Kyoto Protocol allows CO_2 emissions to be offset by marked removal of C from the atmosphere (Kutsch et al., 2009). It is estimated that 73% of the earth’s soil C is stored in forest soils (Rodger, 1993), and mixed evergreen conifer forests in northern California store large amounts of C both above and belowground with 500,000 tons of CO_2 potentially stored in second growth trees over a 100 year period (VanEck, 2016). For this study SOM is defined as including all the organic compounds in soil except living roots, ranging from humus to barely decomposed plant material. Soil organic carbon (SOC) is defined as the C contained within SOM including both particles in the ultimate stage of decomposition and particles dominated by stable compounds adsorbed to mineral surfaces.

Typically 50-58 % of organic matter consists of organic C, depending on whether it is derived from leaf litter, woody debris, or roots (Schmidt et al., 2011). The amount of C decomposed and sequestered is affected by physical, chemical and biological changes in the soil, including the movement of gas and moisture through the soil (Kalbitz & Kaiser, 2008). The amount of C sequestered in an ecosystem maintains a dynamic balance with its environment on a local scale (Lal, 2005). Soil C is a source to the atmosphere when rates of mineralization (i.e. short-term decomposition) are greater than C sequestration rates (long-term storage) (Trumbore & Torn, 2003).

Soil Organic Carbon varies globally depending land use, topography, mean annual precipitation, and mean annual temperature (NRCS 2009). Warmer annual temperatures increase decomposition which decreases SOC amounts. With higher precipitation, plant growth and biomass inputs increase, increasing SOC (Thornley & Cannell, 2001). This variation and complexity of organic matter make studying SOM and SOC on a local level more pertinent.

I divided this study into four main questions:

1) What is the ratio of OC:OM in the soils at this study site?
2) Do the following environmental factors affect SOM? If so, what is the relationship between SOM and these factors?
    a. Depth within a soil profile
    b. Bulk density (the mass of a known volume of soil)
    c. Root content
    d. Distance to tree bole

3) What is the overall C inventory for this study site?
4) How many samples are needed to capture the same amount of variance we captured in SOM to 1 m depth, with appropriate margins of error?

Rationale and Significance

This study is part of an interdisciplinary project within the Humboldt State University Department of Forestry and Wildland Resources, which began in 2014 and was supported by United States Department of Agriculture McIntire-Stennis grant 2015-32100-0682. The collaborative effort was titled "Carbon, water-use, and regeneration after a variable-density retention evergreen mixed conifer forest," and included investigations of tree water use, variable thinning operations, water stress, natural forest regeneration, duff layer inventory, sap flow monitoring, seedling mortality, and overall C pool inventory. The project provided an opportunity for the department to come together and utilize all aspects of the faculty's knowledge in hopes of providing a more complete assessment of the L.W. Schatz Demonstration Tree Farm (LWSDTF), with the potential for results to inform land management decisions elsewhere in the region with respect to C and water dynamics.

SOM:SOC Ratios

Tracking soil C changes over time requires a consistent sampling design and repeated inventories (Kutsch et al., 2009), as it is difficult to predict what conditions influence changes in previously stable and unstable OM (Harrison et al., 2011). These

findings, along with confounding environmental factors, make studying SOM dynamics complex and challenging (Trumbore & Torn, 2003), and were an impetus to develop my own SOC:SOM ratio for the study site while taking a thorough inventory of the SOM and SOC present.

Even though studies have analyzed C pools over time, there is still uncertainty regarding the amount of SOM present and soil C storage possible over large areas considering plant diversity, litter variety, land use, disturbances, and future climate conditions (Jastrow et al., 2005). The 0.58 ratio is widely used to calculate the proportion of organic C in organic matter in mineral soil and 0.48 – 0.50 is commonly used to estimate C in organic biomass, based on assumptions of similar vegetation type, parent material, soil depth, and climate (Ball 1964; Donkin, 1991; Jain et al., 1997; Lunt 1930; Nelson and Sommers, 1982; Waksman & Stevens, 1930). Due to differences in litter quality and quantity, moisture, temperature, microbial community, soil chemical composition, and landscape position, there is inherent spatial and temporal variability of SOM and SOC between and within landscapes (Kutsch et al., 2009). Decomposability of litter and roots varies widely with plant diversity, with deciduous leaves breaking down more rapidly than needles from conifers (De Deyn et al., 2008). Conifer needles have more wax and a thicker endodermis in order to retain moisture more efficiently, and therefore have slower rates of decomposition. This is important here in California where 18 % of land is covered by forests and these forests are dominated by conifers. The amount of SOM present depends on its source; root-derived C is retained in soils longer term than inputs from leaves and needles (Schmidt et al., 2011). Even within one plant

species, litter decomposability can vary according to nutrient and water status (Trumbore, 2000). In order to quantify SOM and SOC on a landscape level more accurately, using different SOC:SOM ratios at different depths and possibly with different soil types and ecosystems can help to refine these quantitative estimates of SOC and SOM over an area.

SOM and Depth

To understand how and where C is stored in soils and the processes that affect OM decomposition, it is important to analyze OM distribution across spatial and temporal gradients in long-term, controlled studies of entire soil profiles to a meter or more depth (Schmidt et al., 2011; Harrison et al., 2011). Organic Matter has a lower rate of decomposition with depth, which may be due to its location rather than inherent chemical and physical properties (Harrison et al., 2011).

The United States Forest Service Forest Inventory Analysis (FIA) protocol only samples to 20 cm depth, and it is possible that this depth underestimates the total soil C present, as the C found below 20 cm depth can exceed aboveground C pools (Harrison et al., 2011). In some cases, the top 0-20 cm of mineral soil contained 27-76 % of the total C in the profile, with an average of 44 % of C in the top 0-20 cm of the soil profile (Homann et al., 2005). Risk et al. (2008) found that soils at 35 cm depth were 100 times less active than surface soils in regard to soil C decomposition, but when put in the same conditions in a laboratory, there were small differences in decomposition rates, indicating that soil activity was mainly due to depth within a profile. Each soil profile tells the story of its own development, but generally soils with the same soil forming factors and vegetation exhibit similar C depth trends (Diochon & Kellman, 2008), and C

concentration typically decreases exponentially with depth (Trumbore, 2000). Researchers wishing to either quantify soil C pools or measure changes of SOC over time are encouraged to sample soil profiles as deeply as possible and not assume that deeper soil horizons are unnecessary for adequate ecosystem analysis (Harrison et al., 2011).

SOM and Bulk Density

Bulk density (D_b) affects soil structure, which is the pattern of individual soil granules clumping or binding together and the arrangement of soil pores between them. High D_b results in decreased pore space and lower aeration within a soil profile, influencing SOM and SOC spatial variation. There are many small-scale habitats within a soil profile connected by water-saturated or unsaturated pore space (Ekschmitt et al., 2008), and these microhabitats could restrict C decomposition if water movement, air movement, root growth, and biological activity are restricted by high D_b.

In the past, D_b and soil depth have been used to estimate soil C, and in some soil types D_b is predicted and soil C is simply extrapolated from these estimates (Huntington et al., 1989). Today, it is generally accepted that D_b must be measured to get an accurate assessment of soil C. Dense soil structures and massive soils with high D_b can lock OM within aggregates where it is protected from mineralization and not available to microorganisms (Jiménez et al., 2008). This may be due to limited oxygen availability for heterotrophic decomposition of SOM. It is also necessary to consider rock content within aggregates since inaccuracy of rock volume measurements when calculating D_b can lead to large uncertainties in determining C inventory (Ravindranath & Ostwald, 2008).

SOM and Roots

Roots are the main interface between trees and the soil ecosystem, taking up water and nutrients from the soil, storing C compounds, providing physical stability for plants, and reflecting the soil's chemical and physical properties and conditions (Iversen, 2010). Root morphology and soil C are affected by physical soil factors such as soil moisture, D_b, soil wetting depth, access to groundwater, depth to bedrock, and soil structure (J. Seney, personal communication, 2016). The effective rooting depth of coarse roots (> 2 mm or larger) is deeper than 1 meter, but the effective rooting depth of medium to fine roots may be limited by horizons with high clay content (Dumm et al., 2008). Dumm et al. (2008) also found an increasing trend in fine root concentrations with depth to 30 cm. Root location determines sites of rhizodeposition and root turnover, which in turn influences the location of microbial activity and soil C storage (Vogt et al., 1995; Hogberg et al., 2001; Nguyen, 2003; Paterson et al., 2007; Koteen et al., 2015). Therefore, the distribution of SOM with depth is strongly related to rooting patterns (Iversen, 2010), and root systems only branch and fork if the production of more root segments will result in a more efficient utilization of soil resources (Fitter et al., 1991).

With the exception of the influence of fine roots, Namm (2012) found that underground biomass could be predicted with the equation:

$$Equation\ 1: ln(biomass) = 6.683 + 0.8149(lnBA)$$

Here, tree basal area (BA) is the strongest predictor of underground biomass. Using this model, a tanoak with average total BA of 0.076 m^2 was expected to stored 98 kg of biomass belowground. Unfortunately, Namm did not determine SOM storage or

fine root biomass in his study of tanoak root biomass at the LWSDTF, where his study was performed. Up to one third of the net primary production in most forests is invested into the formation of fine roots (<2 mm) which provide a large biomass input to the soil and are the most active and dynamic part of the root system (Trumbore and Gaudinski, 2003). Fine root biomass is thought to be a large storage space for belowground C and is of increased importance with soil depth (Jackson et al., 1996; Jobbagy and Jackson, 2000). Understanding the spatial heterogeneity of roots helps us to estimate soil C on a landscape scale, and few studies have characterized root distribution in a way that gives us insight to C inventory and distribution (Koteen et al., 2015).

Fungi

Although it is outside the scope of my project, when discussing root influence on SOM, the influence of mycorrhizae (symbiotic fungi that grow in and around plant roots) should be mentioned. Trees often form mutually beneficial relationships with mycorrhizae, which act as an extended root network and increase the root surface area for amplified nutrient and water uptake. Mycorrhizae secrete enzymes that catalyze the decay of organic matter, thus increasing SOM at any given site. Fresh root inputs may prompt microbial activity in a way that increases decomposition of older organic matter (Schmidt et al., 2011). Broadly speaking there are two common types of mycorrhizae; ectomycorrhizal (EM) and arbuscular mycorrhiza (AM). Averill et al. (2014) found that the type of fungi a tree associates with correlates with the amount of SOM more than climate and soil structure. These studies do not distinguish between the C residing within the fungi in plant roots and the fungi that reside in the bulk soil, but instead identify the

type and species of mycorrhizae present and separately measure the soil C (Averill et al., 2014). These findings support the need to consider how local-scale and micro-scale biotic interactions can shape regional-scale C dynamics.

SOM and Distance from Tree Bole

Trees and shrubs generally concentrate C and nutrients beneath their canopies by depositing plant litter underneath the canopy and transporting nutrients from surrounding areas via their roots (Belsky, 1994; Eldridge et al., 2012; O'Donnell & Caylor, 2012). In areas where savanna and forests merge, significant differences in C and root biomass have been found, both laterally and with depth, as a function of distance from tree bole (Koteen et al., 2015). More C accumulates as trees age and the concentration of C seems to follow root density as it decreases farther from the tree (Koteen et al., 2015).

The relationship between location of tree bole and belowground C was analyzed in this study, but aboveground C from trees, shrubs, litter, and fallen branches is also important in the overall C cycle. Carbon estimates in roots are most commonly found through aboveground measurements of tree diameter at breast height (DBH, measured at 4.5 ft., or 1.4 m) and allometric equations. More recently, remote sensing has been useful and cost-effective in estimating aboveground C on a landscape level, with an average accuracy of 4.7 % error (Ravindranath & Ostwald, 2008). These techniques can be used to track changes in the C stocks of forests over time, when estimating C removed upon thinning or deforestation, and to understand future changes in C stocks (Houghton, 2005).

Hypotheses

Based on previous research, I hypothesized that depth, root density, bulk density (D_b), and distance from tree bole are all significant predictors of SOM. More specifically, my study investigated the following hypotheses:

1) Soil organic matter decreases with soil depth.
2) Soil organic matter decreases as bulk density (D_b) increases.
3) Soil organic matter increases as root density increases.
4) Soil organic matter decreases with increased distance from tree bole.

MATERIALS AND METHODS

Site Description

My study site is located within the L.W. Schatz Demonstration Tree Farm (LWSDTF), a demonstration forest near Maple Creek in Humboldt County, California (Figure 1). The 148 ha tree farm is located in the Klamath Mountains Geomorphic Province, 40 km inland at N40°46’49”, W123°52’21” (Figure 2). The Mediterranean climate is characterized by hot, dry summers averaging 29^{o} C and cool, wet winters averaging 8 ^{o} C. Average annual precipitation is approximately 120 cm, with the majority falling as rain between the months of November and March (Western Regional Climate Center, 2000). The tree farm was used for intensive timber harvesting in the 1950s, leaving a secondary succession forest before being donated to Humboldt State University in 1987. This non-industrial tree farm is currently used for research in forest operations, forest restoration, watershed monitoring, and experimentation.

Figure 1. Location of L.W. Schatz Demonstration Tree Farm within Humboldt County, CA (shaded region).

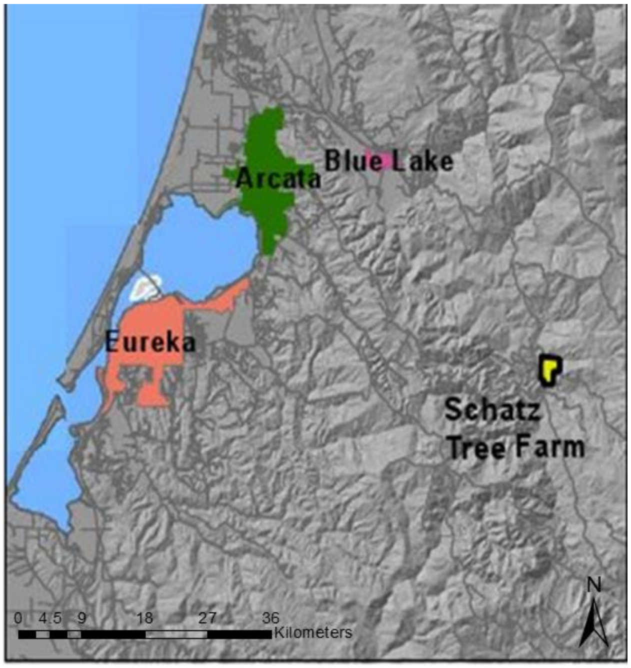

Figure 2. Location of L.W. Schatz Demonstration Tree farm in relation to Eureka, Arcata, and Blue Lake. Courtesy of HSU Forestry Department.

My study site was located on the north side of the ridge, near Davis Creek Road (Figure 3). There are several ridges within the LWSDTF, and slope varies throughout the tree farm with a downhill trend from east to west. The elevation of the tree farm ranges from 153 m to 330 m, and is approximately 242 m at my study site, with a 35 % north-facing slope. The forest floor is heterogeneous comprised of coarse woody debris, moss mats, and litter, averaging 5 cm depth in the O horizon (NCSS, 2016).

Figure 3. Location of study site within L.W. Schatz Demonstration Tree Farm, aerial view. Courtesy of HSU Forestry Department.

Geologic parent material for the LWSDTF is comprised of colluvium and residuum derived from greywacke (sandstone) and mudstone (J. Seney, personal communication, 2016). In a conifer-dominant forest with heavy precipitation, this geologic parent material has weathered into a well-drained, fine-medium textured acidic soil. The soils at this site are in the Ultisol soil order (NRCS, 2008), which are strongly leached acidic forest soils. Ultisols have relatively low native fertility, but are found mostly in humid temperate and tropical areas and can support productive forests due to the favorable climates where they are found (McDaniel, 2012). Ultisols have a subsurface horizon where moisture and nutrients, including SOM, are held and in which

clays have accumulated, often with strong yellowish or reddish colors resulting from the presence of iron oxides. Full pedon descriptions (Table 5 and Table 6 in Appendix A) found iron concentrations at 90-100 cm depths in the east trench, possibly due to a seasonally high water table depth causing increased compaction and D_b from legacy timber harvest and road construction impacts (J. Seney, personal communication, 2016).

The Natural Resources Conservation Service (NRCS) soils map unit 464 was mapped in my study area and represents the soils at this study site. Map unit 464 is called the Mooncreek-Tossup-Noisy complex (40% Mooncreek soils, 20 % Tossup soils and 15% Noisy soils) (NRCS, 2008). The clay percent in this map unit ranges from 16-27 % in the A horizon, 23 – 35 % in the upper Bt horizon, and 30-40 % in the lower Bt horizon, and textures generally trend from clay loam to silt clay loam from 50 to 100 cm depth. The clays at my site are most likely vermiculite in upper horizons fading to kaolinite with depth and may include small amounts of gibbsite as well (NRCS, NCSS 2016). The soils at my study site display characteristics of the Mooncreek soil series (Table 4 in Appendix A), which are fine-loamy, mixed, active, Xeric Palehumults (J. Seney, personal communication, 2016; NRCS, 2008). This is a very common soil type along mountain slopes and ridges on the North Coast in Douglas-fir-tanoak forests in northern Humboldt and Del Norte counties. See Appendix A for the NRCS full pedon description, as well as descriptions provided by Humboldt State University undergraduates.

As part of other research efforts taking place at the LWSDTF, variable density retention logging operations and removal of slash took place on 0.04 ha experimental plots in November of 2014. On January 21, 2015, a backhoe was used to dig two trenches to expose soil profiles of approximately 5 m wide by 1.5 m deep, with the west trench in close proximity to the experimental plots and the east trench located approximately 100 m from these plots. Trench sites were selected according to distance from tree bole, backhoe access, and ability to represent LWSDTF soils. The trenches were close enough to existing vegetation to analyze root distribution, while maintaining sufficient distance from trees to avoid tree mortality. The east trench is parallel to Davis Creek Road and parallel to the slope contours (Figure 4).

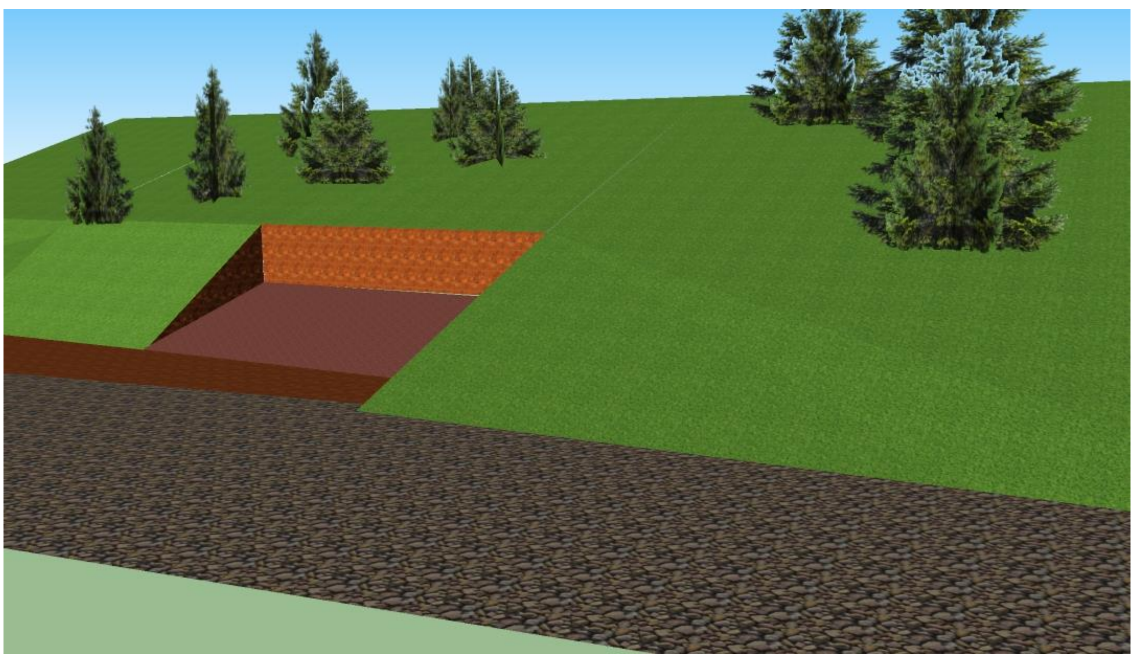

Figure 4. Depiction of east trench, true to scale, parallel to the road and cut into the hillside.

The west trench is perpendicular to the road and perpendicular to slope contours, cutting into a small ridge (Figure 5).

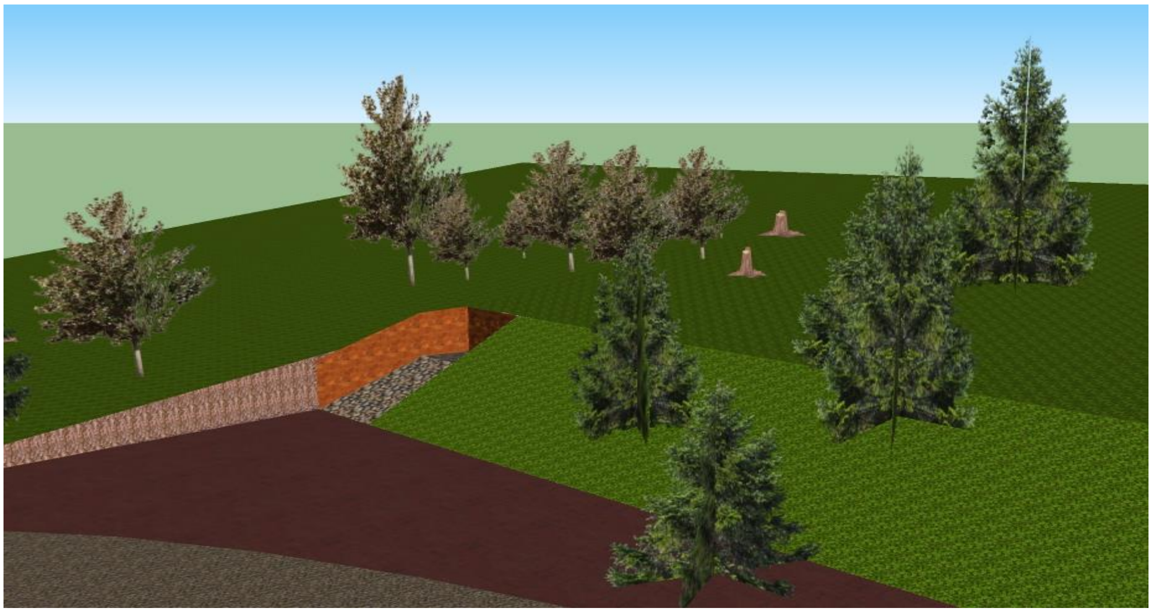

Figure 5. Depiction of west trench, true to scale, perpendicular to the road and cut into the hillside.

Vegetation Mapping

Trees larger than 6 cm DBH within 10 m of the trench were mapped (Figure 4 and Figure 5) using an open reel tape, identified to species, and DBH was recorded (Table 7 in Appendix C).

To create a consistent variable to represent distance to tree bole for each column location within the trench, I indexed each tree individually by dividing DBH by distance from the top of each column in the trench, and averaged these indexes by number of trees

within 10 m of each trench (Equation 2). I analyzed the relationship between averaged indexed distance from tree bole (D_{tb}) and OM %, with the distance remaining constant for each column.

$$Equation\ 2:\quad D_{tb} = \frac{\sum\left(\frac{DBH}{distance\ (m)}\right)}{\#trees}$$

Where D_{tb} is the averaged indexed distance to tree bole.

Sample Selection

Belowground SOM was mapped adjacent to the root system of four tree species, Douglas-fir (*Pseudotsuga menziesii,* Mirb.), tanoak (*Notholithocarpus densiflorus,* Hook. & Arn.), grand fir (*Abies grandis,* Dougl. Ex D.Don), and California bay (*Umbellularia californica,* Hook. & Arn.). I sampled soils in both trenches using a 1 m x 1 m soil profile grid made out of PVC pipe that was then divided into 100 one dm^2 squares with tensile wire to guide in selecting spatially representative soil samples. In the east trench I sampled three horizontal placements of the m^2 grid frames on the trench wall and one smaller 80 cm by 50 cm grid. In the west trench I sampled four horizontal placements of m^2 grid frames on the trench wall. The m^2 grid replicates were labeled alphabetically with animal names, the rows of each grid were labeled alphabetically, and the columns were labeled numerically (Figure 6 and Figure 7). I chose this method of sampling to assess the effect of depth, bulk density (D_b), root distribution, and distance from tree bole on SOM (Achat et al., 2008).

Figure 6. Representation of soil sampling in east trench by m^2 grid. Grids were named in alphabetical order. The Antelope grid was 50 cm by 80 cm, sampled from a soil pit to the left. Other grids were divided into 100 dm^2 (0.01 m^2). X= full dm^3 volume sample; P= partial volume sample, O= no sample taken due to slope change.

Figure 7. Representation of soil sampling in west trench by m^2 grid. Grids were named in alphabetical order and divided into 100 dm^2 (0.01 m^2). X= full dm^3 volume sample; P= partial volume sample, O= no sample taken due to rock layer.

From January 24 to January 30, 2015, soil samples were extracted using a stainless steel cubic decimeter (dm^3) soil extractor custom made by the HSU machine shop, paired with a three inch putty knife to extract each dm^3 sample. Orange golf tees were used to mark each row and column corner with the m^2 grid in place. Once the grid was removed, the dm^3 extractor was hammered into the trench face and the sample was taken out and put into gallon-size plastic freezer bags, labeled according to trench, grid, row and column. When necessary an 18 V battery-operated reciprocating saw was used to extract large roots that occurred within my samples, but most roots within my samples were removed with pruning shears. In the east trench I extracted full dm^3 volume samples from odd-numbered columns, and took partial volume samples from even-

numbered columns, except where soil material was absent due to slope change. In the west trench I took full dm^3 volume samples from the even-numbered columns, except where inextricable due to a rock layer at the bottom of the profile, a suspected lithologic discontinuity in the soil profile. All full volume samples were extracted using the dm^3 sideways-coring method described above, and all partial samples were extracted similarly, without full insertion of the soil extractor. This method yielded 300 samples from the east trench, consisting of 162 full volume samples and 138 partial volume samples, and 174 full samples from the west trench, totaling 474 soil samples. Table 11 in Appendix C lists the number of full and partial volume samples taken from each grid by depth interval.

Sample Storage

Samples were organized into ice chests and crates for transportation to the Humboldt State University Forestry Department walk-in freezer. Samples were stored in the freezer at 4^{o} C and processed between February and May of 2015.

Loss on Ignition

Samples were air dried in the HSU forestry greenhouse and oven dried at 105^{o} C for a minimum of 24 hrs to eliminate any moisture present in the samples. After drying, three replicates of approximately 5 g each were weighed out for loss on ignition (LOI) analysis. These replicates were lightly crushed with mortar and pestle, sieved through a 2 mm sieve, put through a sample splitter, placed in 15 mL crucibles and weighed to the

nearest 0.01 g. LOI tests were performed on all three replicates. The LOI analysis is a routine procedure for estimating SOM by measuring the loss of weight in a sample before and after being heated to 375° C for 16 hrs.

Bulk Density

The dm^3 extractor volume was not accurate enough to use in bulk density calculations, partially due to extractions being slightly larger than dm^3, and partially due to the rock content that is difficult to trim from the edges of the dm^3 shovel. The coated clod method was used to determine D_b value according to standardized methods (Blake 1965**).** The details of these calculations are in Equation 6 in Appendix C. I was unable to measure D_b in all 474 samples due to lack of intact clods in all samples. D_b was measured for 187 samples.

Rock fragments (>2 mm in diameter) were accounted for within each sample by crushing a similar sized clod and extracting all rocks. The volume of these rocks was measured by placing a known volume of water into a graduated cylinder, adding rocks, and noting the amount of water displaced. This rock volume and rock mass were subtracted from the original D_b value so there was an estimated rock-free D_b.

Root Extraction

I chose samples for root extraction based on sample location within each trench, to ensure I had root samples from all horizons. I used an *a priori* spatial pattern to prevent bias on sample choice (Figure 8 and Figure 9). If the intended sample was

unavailable due to prior destructive data collection, the sample to the right or directly below was chosen. All samples from Antelope grid were processed for roots, and some grids had more samples selected for root extraction based on availability. An average of 26 samples from each grid were selected for root extraction, totaling 207 root extractions.

	1	2	3	4	5	6	7	8	9	10
A	X				X				X	
B			X				X			
C	X				X				X	
D	X		X				X		X	
E					X		X			
F			X				X			
G	X				X					
H			X						X	
I	X						X			
J			X		X				X	

Figure 8. Spatial pattern of samples with roots extracted in east trench

	1	2	3	4	5	6	7	8	9	10
A		X				X				X
B				X				X		
C		X				X				X
D		X		X				X		X
E						X		X		
F				X				X		
G		X				X				
H				X						X
I		X						X		
J				X		X				X

Figure 9. Spatial pattern of samples with roots extracted in west trench

Roots were processed as described in the Natural Resource Conservation Service guide (NRCS nd). The entire soil sample including roots was weighed to the nearest 0.01 g, oven dried at 105^{o} F for 24 hrs, weighed again, and left to soak in a sodium hexametaphosphate (NaHMP) solution (100 g L^{-1} concentration) for 12-16 hrs, which

helps disperse soil particles that continue to cling to roots (Levy et al., 1991). Roots floating on top were picked out by hand with tweezers and the remainder were sieved out using a No. 18 ASTM (1 mm) sieve, and also picked out by hand. Roots less than 1 mm diameter were not collected. Roots were repeatedly rinsed to remove any remaining mineral soil particles and were oven dried at 68^{o} C for 16 hrs and weighed to the nearest 0.01 g.

Carbon Analysis

In total, 474 soil samples were processed for organic matter (OM) % using loss on ignition (LOI), and of these, 95 samples were sent to the Oregon State University (OSU) Analytical Lab for combustion analysis of organic carbon (OC) %. I chose 50 soil samples from the west trench and 45 samples from the east trench, according to spatial representation and budget constraints. Based on the same criteria, I sent 57 root samples to the OSU lab for C analysis, with 28 samples from the west trench and 29 samples from the east trench. I processed 21 of these root samples for OM % using LOI analysis.

After accounting for three outliers that had higher OC % than OM% and therefore thought to be due to transcription error, I compared the percent OC % found by the OSU lab with the OM % I found from LOI tests for both soil and root samples.

Statistical Analysis

The final dataset that I tested included multiple subsets of data including: OM % by LOI, location of each soil sample within the trench, D_b (g cm $^{-3}$), root mass (g dm^{-3}), SOC % by combustion (%), root C by combustion (%), root C by LOI (%), and average distance to tree bole index (m).

I collected OM % data on 474 samples, and used subsets of this data set to analyze the relationships between OM % and each predictor variable individually and collectively. I created depth functions to 1 m depth to visually represent the patterns of SOM %, D_b, rock content, root presence, SOM kg ha^{-1}. I illustrated the kg SOM ha^{-1} and kg SOC ha^{-1} present in 10 cm depth intervals with stacked bar graphs.

I determined the variables most associated with OM % using a generalized linear mixed model (GLMM) and gamma distribution with the *lme4* package (Bates et al., 1994; Grothendieck, 2014). Given the non-normal nature of OM % distribution and the nested structure of measurements taken from each soil sample, this statistical approach seemed appropriate. GLMMs and gamma distribution have been successfully used in previous soil studies modeling soil respiration in forests (Suchewaboripont et al., 2015). OM % was the response variable for all models, and all models included a log link function in the gamma distribution family. All statistical analyses were performed in the program R (R Development Core Team 2016).

Horizontal location (i.e. column) was included as a random effect. Akaike's information criterion (AIC) was used for model selection, and differences in model fit were indicated by a change in AIC values of 2 or greater (Burnham & Anderson, 1998).

To avoid issues of multicollinearity, highly correlated predictor variables were not included in the same model and were identified by a variance inflation factor (VIF) greater than 10 (Burnham & Anderson, 1998).

The first model tested was the full model which included bulk density, roots, average distance to tree bole, and location. In all, I analyzed nine models for OM %. Within the top model I provided an estimate of model accuracy and precision by calculating the root mean squared error (RMSE) and the coefficient of determination (R^2) for the relationship between predicted values and actual values of OM %.

To determine the influence of each variable, I calculated the standardized coefficients for each variable based on the fitted GLMM using the following equation:

$$Equation\ 3: \qquad \beta_{s1} = \beta_1 \times \frac{s_1}{s_y}$$

The standardized coefficients represent the relationship between the predictor variable and the response variable if all variables had the same units, Where β_{s1} is the standardized coefficient for variable 1, β_1 is the unstandardized coefficient estimate for variable 1, s_1 is the standard deviation for variable 1, and s_y is the standard deviation for the response variable. I also calculated model accuracy by calculating the RMSE and R^2 for the top model. All statistical analyses were performed in the program R (R Development Core Team 2016) and Microsoft Excel, and where applicable, statistical analysis was tested at Level of Significance α = 0.05.

SOM and SOC Inventory

I was able to calculate OM in kg m $^{-2}$ when I took D_b and rock fragments into account. OM % was converted to OM kg m $^{-2}$ (Equation 4).

$$Equation\ 4: \left(\frac{OM\ \%}{100} * \frac{g}{cm^3} * \frac{kg}{1000g} * 10cm * \frac{10{,}000\ cm^2}{1\ m^2}\right)$$

I averaged OM kg m^{-2} at each 10 cm depth interval for each grid and for each trench, with all samples taken from the corresponding interval. I multiplied OM kg m^{-2} amounts by the appropriate OC:OM ratio according to depth for SOC kg m^{-2} amounts. These estimates can be more useful when looking at soils on a regional scale and when making land use decisions.

Sample Size

Part of my methodology in having large sample sizes was to calculate the number of samples needed to capture the same amount of variance in OM % that I found at this study site at each depth interval (Equation 5).

$$Equation\ 5: \quad predicted\ sample\ size = \frac{(t * standard\ deviation)^2}{margin\ of\ error}$$

I used 1.96 for the *t*-value, and chose the smallest margin of error that calculated a sample size between 1 and 20, with the exception of the top depth interval in the east trench and the second depth interval in the west trench. This method resulted in larger margins of error for horizons with higher variability; I used a margin of error of 3.0 for depths of 0 to 20 cm, 0.70 for depths 20 to 40 cm, and 0.30 for depths 40 to 100 cm.

RESULTS

SOC:SOM Ratios

There is a positive correlation between SOM and SOC, and SOM is a strong predictor of OC (Figure 10). Points with more than 4% organic C represent samples taken from top horizons. The average ratio of SOC:SOM was 0.45 and varied with depth. The SOC:SOM ratios calculated using LOI OM % and OC % from combustion by the Oregon State University lab ranged from 0.20 to 0.97 including outliers with an average of 0.45. The average ratio in the top two soil horizons (0-20 cm depth) was 0.41, and this ratio increased to an average of 0.49 in deeper soil horizons (20-100 cm depth).

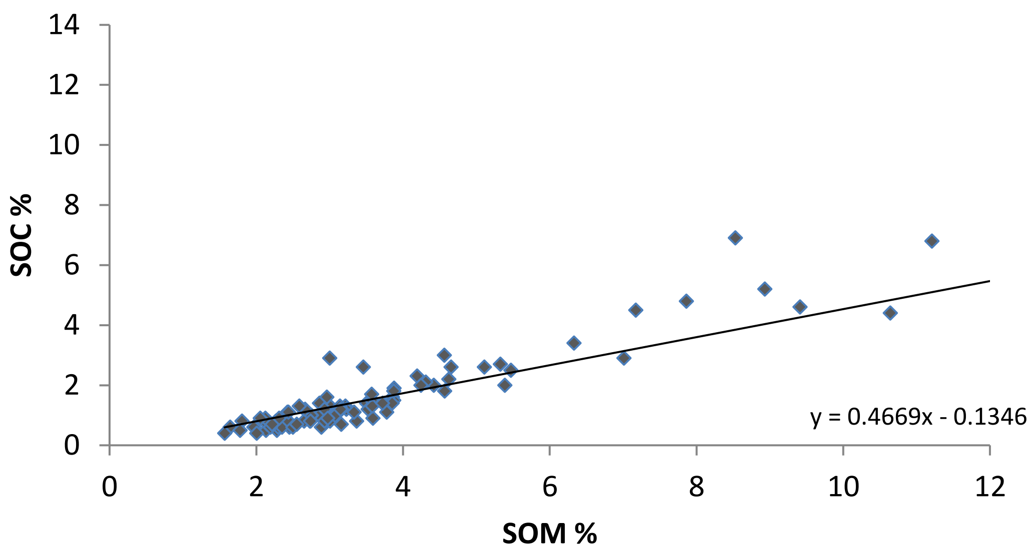

Figure 10. The relationship between soil organic matter (SOM) % and soil organic carbon (SOC) %, *n*= 92.

SOM and Depth

The pattern of decreasing SOM % with depth in both trenches supports hypothesis 1 (Figure 11 and Figure 12). The Antelope grid was only sampled to a depth of 45 cm, and located in order to avoid tree mortality. The increased SOM % at the top horizon for the Bison grid is due to a thicker duff layer which was approximately 15 cm thick.

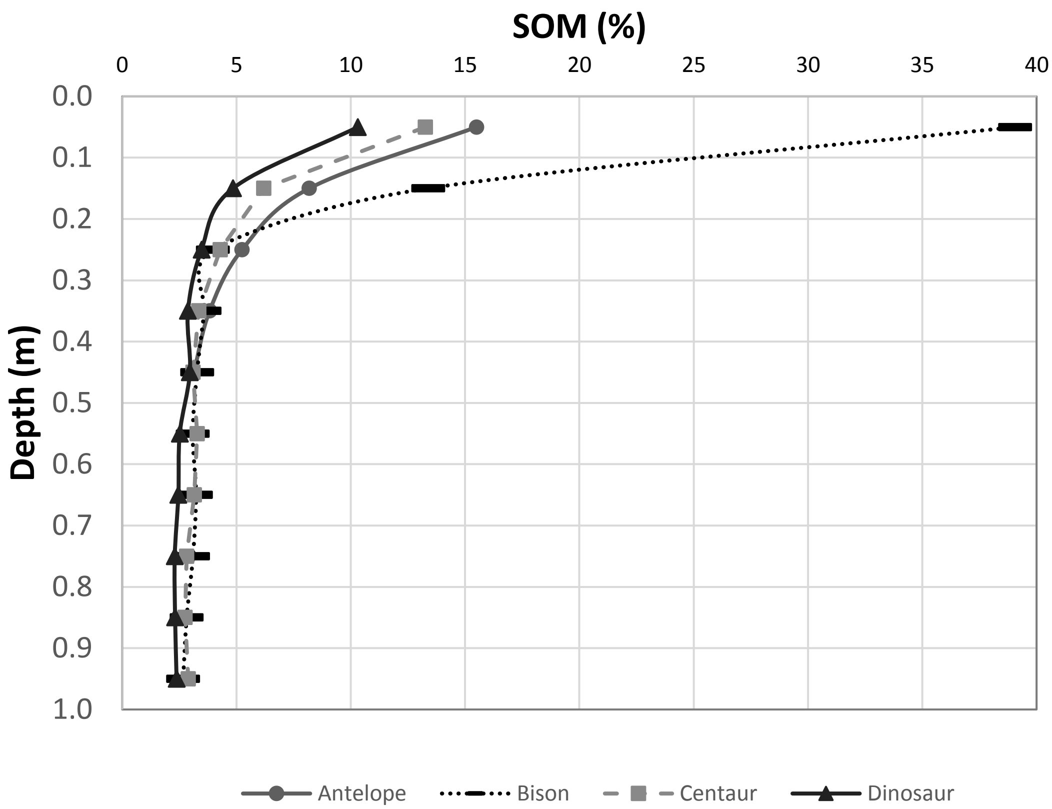

Figure 11. The relationship between soil organic matter (SOM) % and depth to one meter in the east trench. Each data point represents an average of OM% from all samples taken at that 10 cm depth interval. SOM % is not corrected for bulk density or rock content. Table 12 in Appendix C lists sample size for each average.

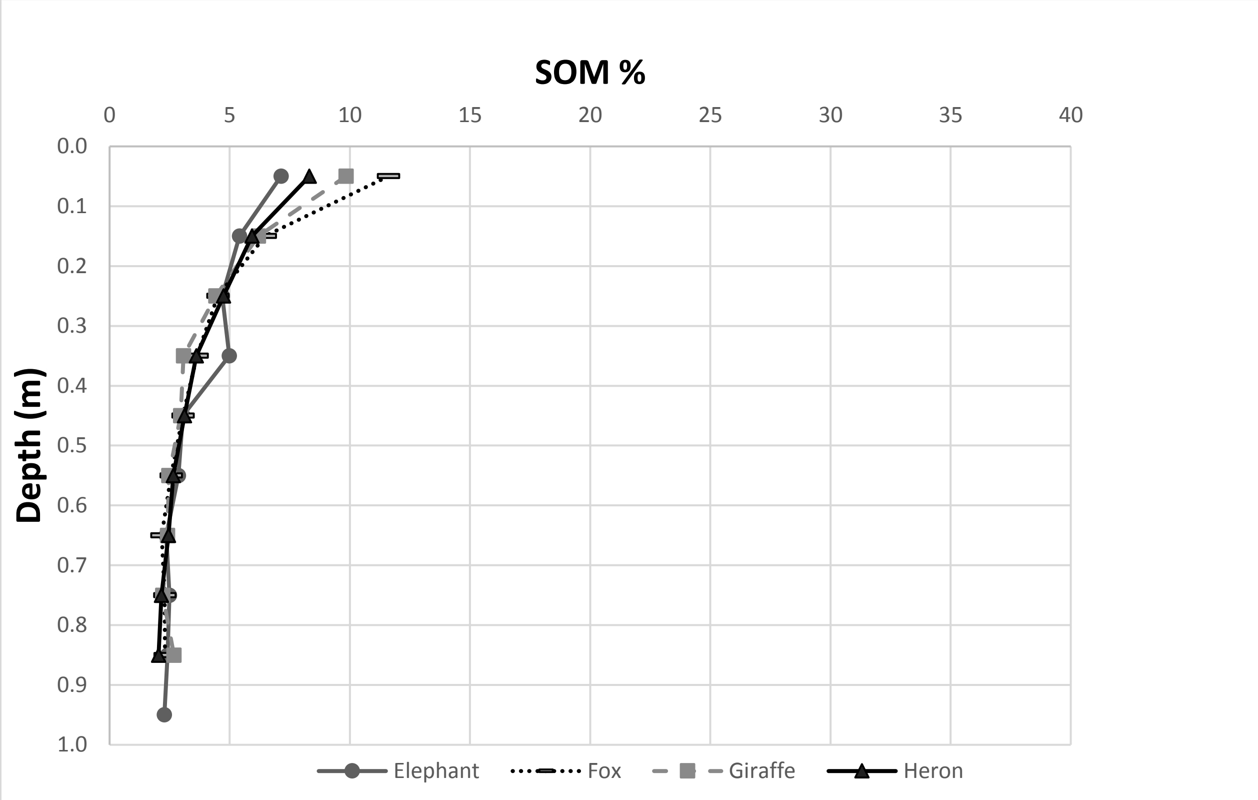

Figure 12. The relationship between soil organic matter (SOM) % and depth to one meter in the west trench. Each data point represents an average of OM % from all samples taken at that 10 cm depth interval. SOM % is not corrected for bulk density or rock content. Table 12 in Appendix C lists sample size used for each average.

The decrease in SOM with depth varies between the two trenches to a depth of 40 cm, but the values are similar at 40-100 cm depths. The east trench had 52% more SOM in the 0-10 cm horizon, mostly due to the high OM% in the Bison grid, had 23% more SOM in the 10-20 cm horizon, and 6% more SOM in the 20-30 cm horizon.

SOM and Bulk Density

Of the 474 samples processed for OM %, I collected bulk density (D_b) data on 187 soil samples. Rock-corrected D_b increases with depth as expected in both trenches (Figure 13), but rock content varied between the two trenches and increased considerably in the west trench (Figure 14). The rock volume began to increase at the 50- 60 cm depth interval in the west trench, with about 7 cm^3 dm^{-3} of rocks, then increased to 17 cm^3 dm^{-3} at 80- 90 cm depths.

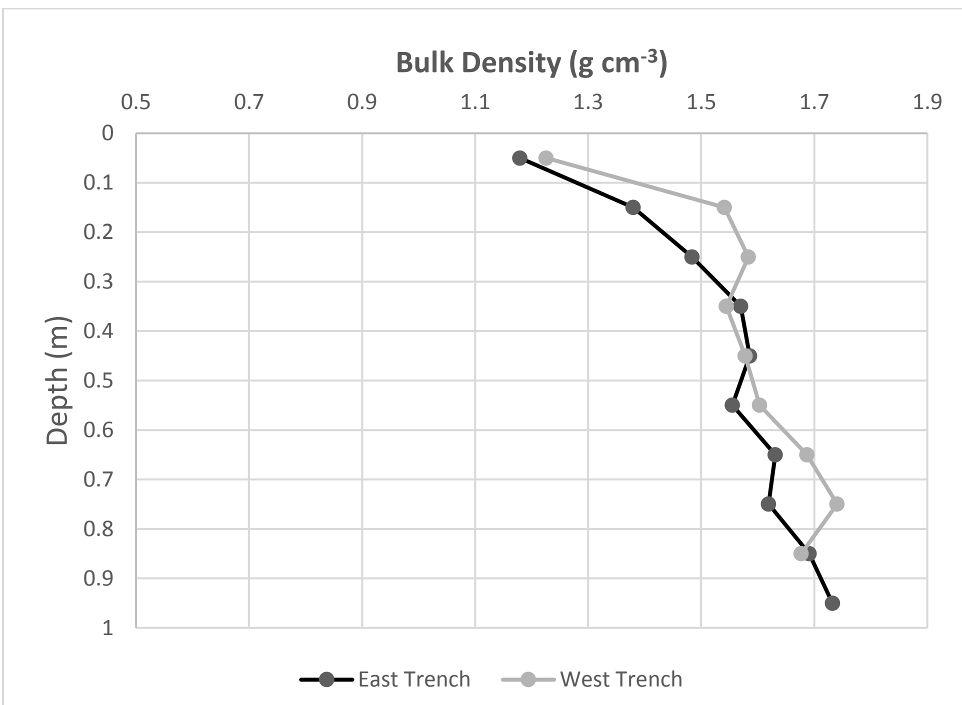

Figure 13. Average fine-fraction bulk density by soil depth in the east and west trench.

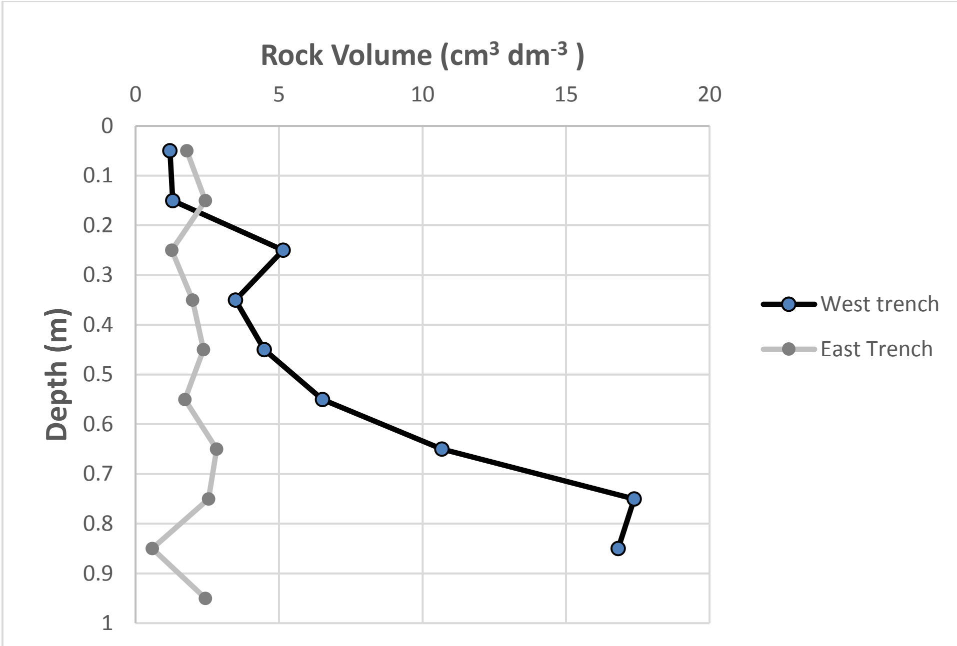

Figure 14. Rock volume (cm^3 dm^{-3}) averages by depth for east and west trench

There is a negative but weak correlation between OM % and bulk density, and the relationship is not as strong as expected (Figure 15). There are many values with similar D_b values, so the data is grouped by 20 cm depth intervals to help with visualization.

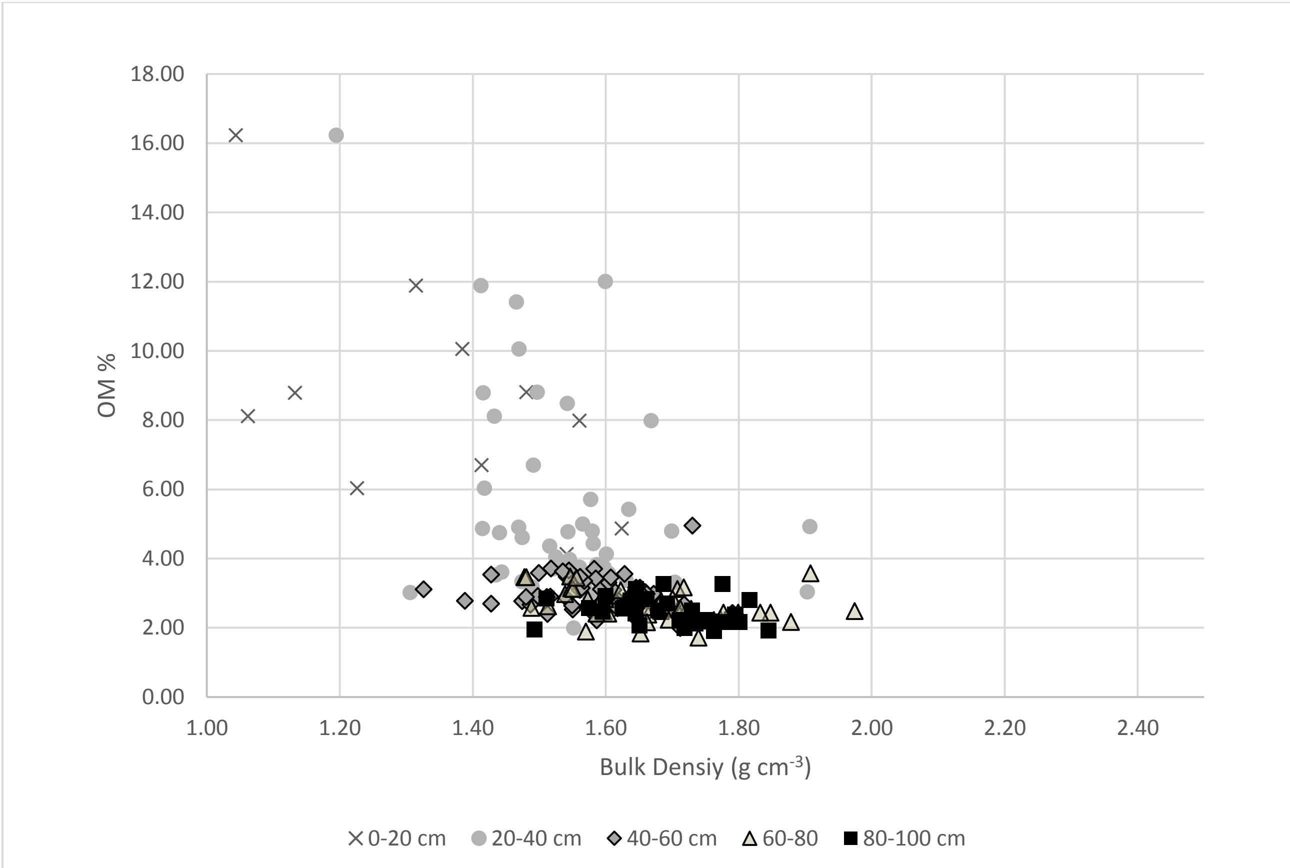

Figure 15. The relationship between organic matter (OM) % and bulk density (g cm^{-3}). The four data points on the far right have higher than expected bulk density, and were taken from mid-level and bottom-level rows in the west trench (Heron G10*, D10*, C10*, Giraffe G8*).

SOM and Roots

I extracted roots from 207 soil samples, and after accounting for three outliers with higher than 50 g roots due to one large piece of root in a sample found at depth, I analyzed the relationships between SOM and dried root biomass. Hypothesis 2 is supported by an increase in SOM % with root content (Figure 16).

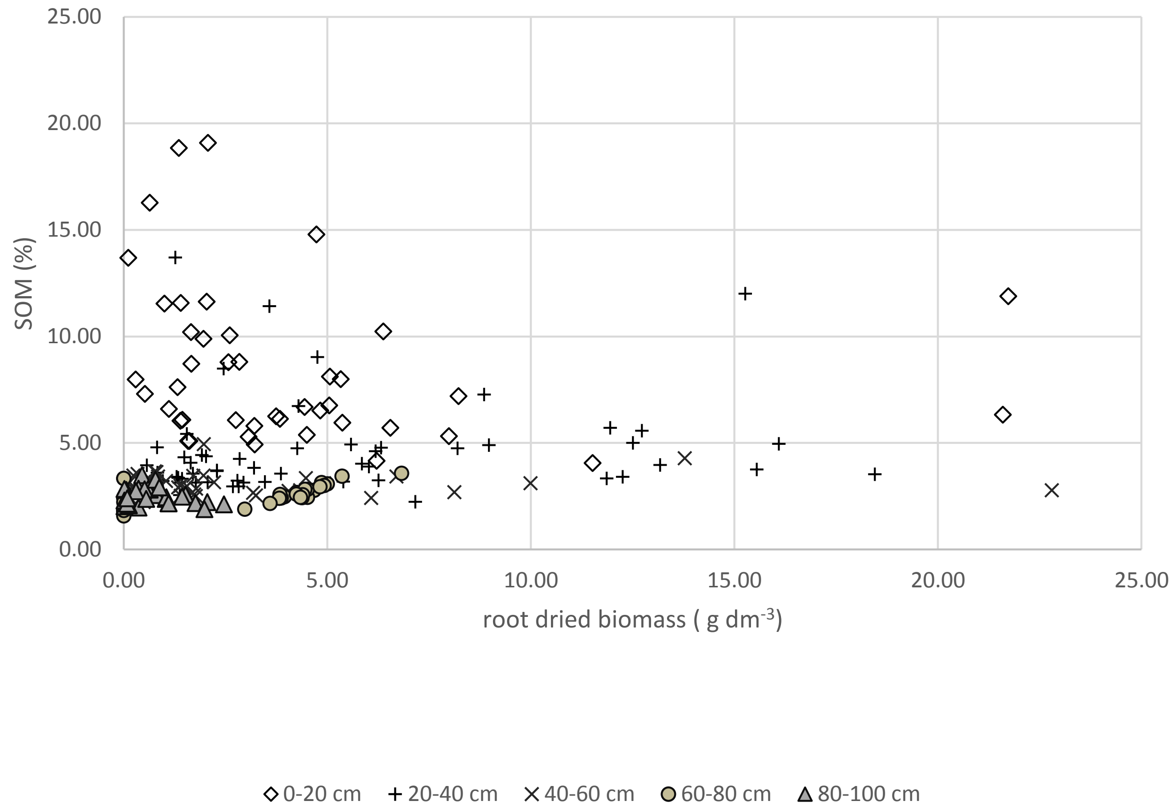

Figure 16. The relationships between soil organic matter (SOM) % and dried root biomass (g dm^{-3}) in both trenches by soil depth, *n* =207.

Root content decreases with depth, with a peak of root biomass at 20 and 30 cm depth (Figure 17 and Figure 18). A decrease with depth appears as expected, which is similar to the trend in OM % with depth.

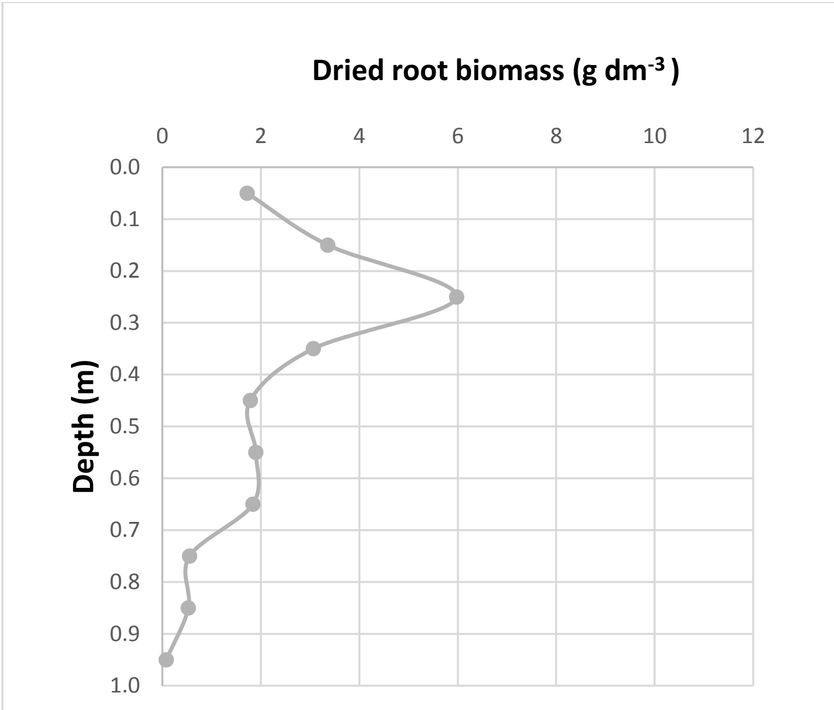

Figure 17. Dried root biomass (g dm^{-3}) to 1 m depth in the east trench. Data points represent an average of root weights at depth intervals of 10 cm in the east trench. Table 15 in Appendix C lists sample size used for averages at each 10 cm depth interval in both trenches.

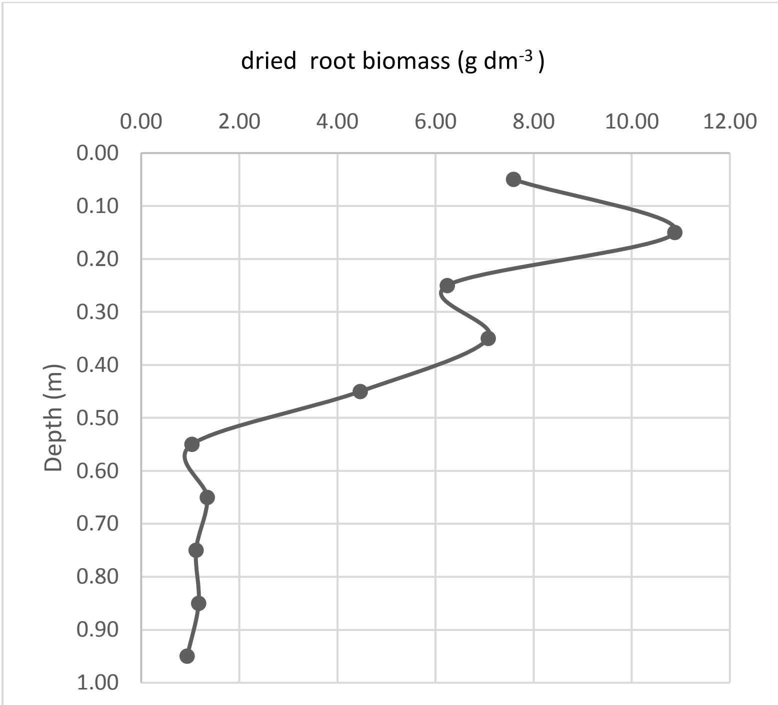

Figure 18. Dried root biomass (g dm^{-3}) to 1 m depth in the west trench. Data points represent an average of root weights at depth intervals of 10 cm. Table 15 in Appendix C lists sample size used for averages at each 10 cm depth interval in both trenches.

Of the 207 root samples extracted, 54 samples were sent to OSU analytical laboratory for C analysis, and 21 of these samples were also processed for OM % using loss on ignition analysis. There is a strong positive relationship between root OM % and root OC %, with an R^2 of 0.81, and an average OC:OM ratio of 0.48 (Figure 19).

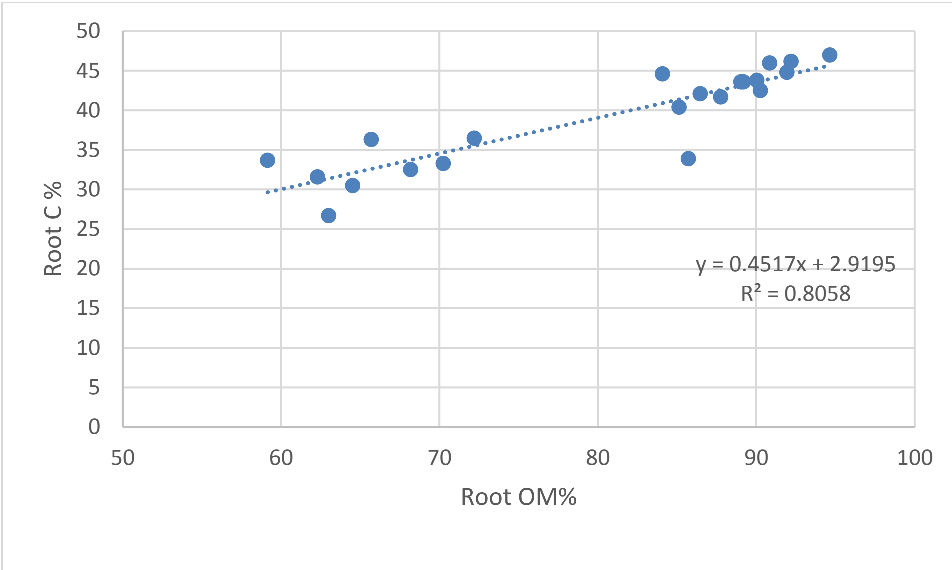

Figure 19. Relationship between root organic matter (OM) % and root organic carbon (OC) %. Data points represent samples from both trenches, *n* =21.

SOM and Distance from Tree Bole

The relationship between averaged indexed distance from tree bole (D_{tb}) and OM %, shows a slight increase with distance from tree bole (Figure 20). This does not support hypothesis four, and instead is contradictory. All 474 samples with OM % data are represented here, with each samples' respective indexed averaged distance to tree bole as calculated from the top of the column in each trench.

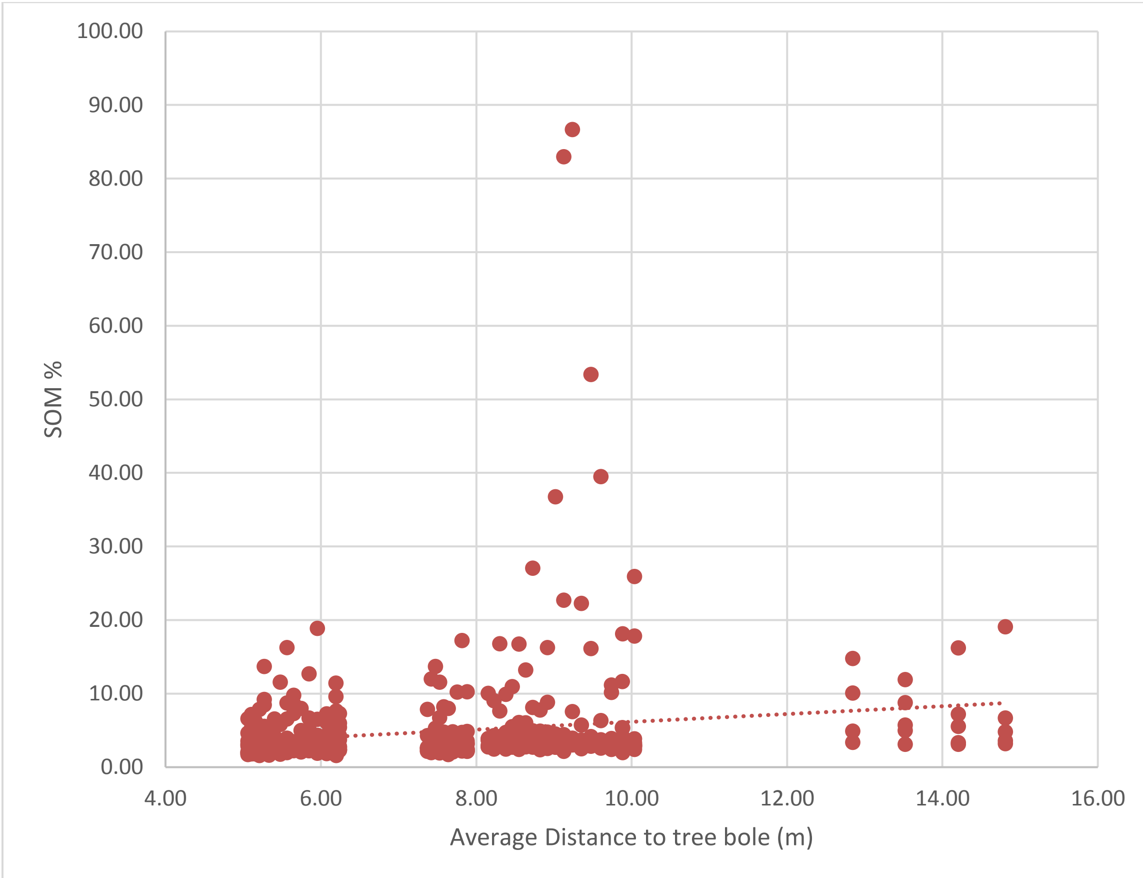

Figure 20. The relationship between average distance to tree bole and soil organic matter (SOM) %. *n* = 474.

SOM Statistical Models

The best generalized linear mixed model (GLMM) for OM % was the full model, including bulk density (D_b), depth interval (depth), amount of roots present, average distance to tree boles (distance), and horizontal position within the trench (location) as a random variable. Models that did not take all of these predictor variables into account

had substantially higher AIC values (> 2) when compared to the full model. In all, I analyzed nine models for OM % and report the top three models (Table 1).

Table 1. Generalized linear mixed models (GLMM) for organic matter (OM)%. Predictor variables included bulk density (Db), depth interval (depth), roots present, average distance to tree boles (distance), and horizontal position in the trench (location) as a random variable, and in some models the interaction term between bulk density (D_b) and depth interval (depth), n = 187.

OM % Models	**K**	**AIC**	**Δ AIC**	**LOGLIKELIHOOD**
(Full model) D_b+ roots + distance + depth + location	6	339.3	0.0	-162.6
roots + distance + depth + location	5	341.4	2.1	-167.7
D_b+ roots + depth + location	5	343.4	4.1	-165.7

Note: K is the number of parameters, Δ AIC is the difference in AIC score from the top model

For the top model, root- mean-squared error (RMSE) is 1.34 and the coefficient of determination (R^2) is 0.69 m which measures the difference between predicted values and actual values of OM % (Table 2).

Table 2. Best generalized linear mixed models (GLMM) for organic matter %. The best model with the lowest AIC score included the bulk density (D_b), depth interval (depth), amount of root material present, average distance to tree boles (distance), and horizontal position within the trench (location) as random variable

Top OM% predictor model			***R*² =0.69**	**RMSE = 1.34**	
Random effects	**Variance**	**Standard deviation**			
location (intercept)	0.02562	0.1601			
Residual	0.08220	0.2867			
Fixed effects	**Coefficient estimate**	**Standard error**	***p*-value**	**Standardized coefficient estimate (β)**	**VIF**
Intercept	2.19284	0.39998	<.0001	0	---
D_b	-0.50980	0.25248	0.0435	-.03240	1.85277
Roots	0.00658	0.002657	0.0133	.03485	1.19363
Distance	.03385	0.01366	0.0132	.03845	1.13139
Depth	-0.97111	0.14080	<.0001	-.09753	1.81764

Note: R^2 is based off the relationship between actual and predicted values, RMSE is the root mean square error, and VIF is the variance inflation factor.

Based on the standardized coefficients, depth had the strongest association with OM % (β= -0.09753). Bulk density (β= -0.03240), roots (β=0.03485) and distance (β= 0.03845) had weaker association with OM %, which correlates with my data depictions (Figure 10 through Figure 20). These trends represent the relationship of each predictor variable if all other variables are held constant (Figure 21).

The R^2 between predicted and actual values of OM % was 0.69, and the root mean squared error was 1.34. To illustrate the GLMM, scatterplots A through D represent the

relationship of OM % and each predictor variable individually while taking the mean value for the other three predictor variables (Figure 21).

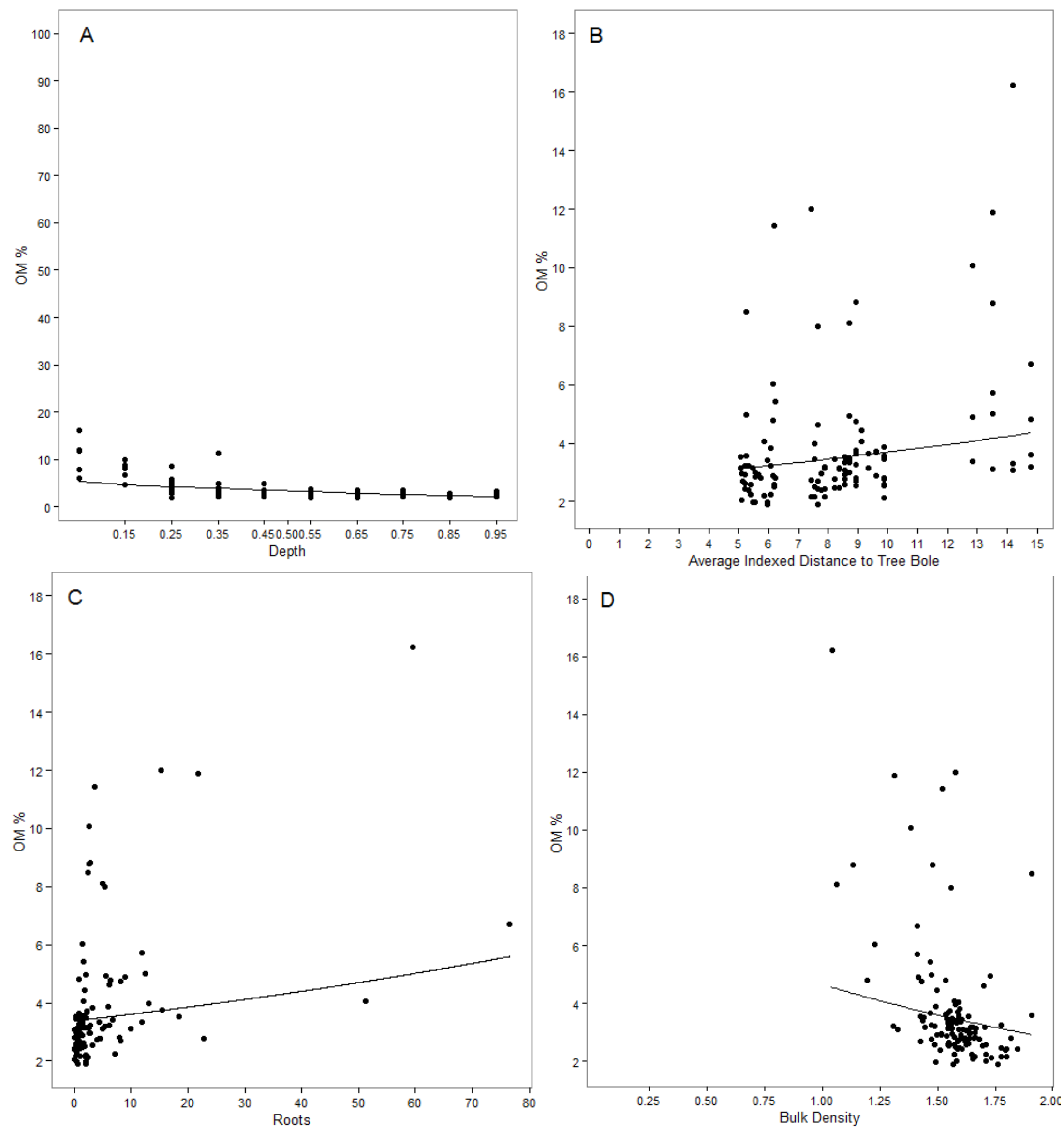

Figure 21. Scatterplots showing the relationship of organic matter (OM) % with depth (A), distance from tree bole (B), roots (C), and bulk density (D). Models are calculated using the coefficient estimates from the top model for OM % and represent the relationship of each predictor variable individually while taking the mean value for all other predictors.

SOM and SOC Inventory

When separated by grid within each trench, OM kg m^{-2} varies slightly more in the west trench than in the east trench. (Figure 22 and Figure 23). These patterns are similar to the patterns of OM % with depth.

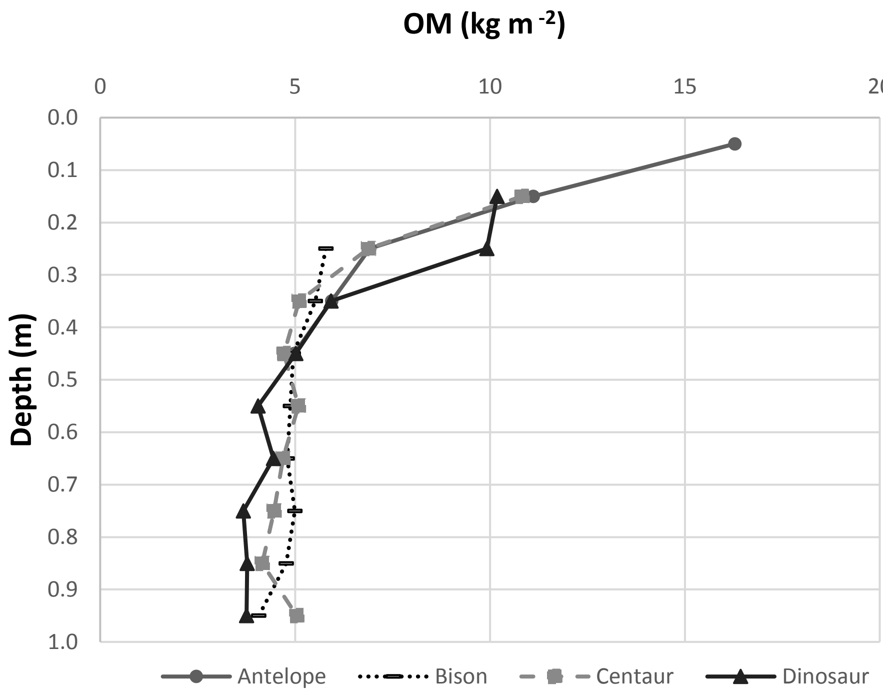

Figure 22. Soil OM kg m^{-2} by depth in the east trench, corrected for fine-fraction bulk density. Table 13 in Appendix C lists sample size used for averages at each 10 cm depth interval.

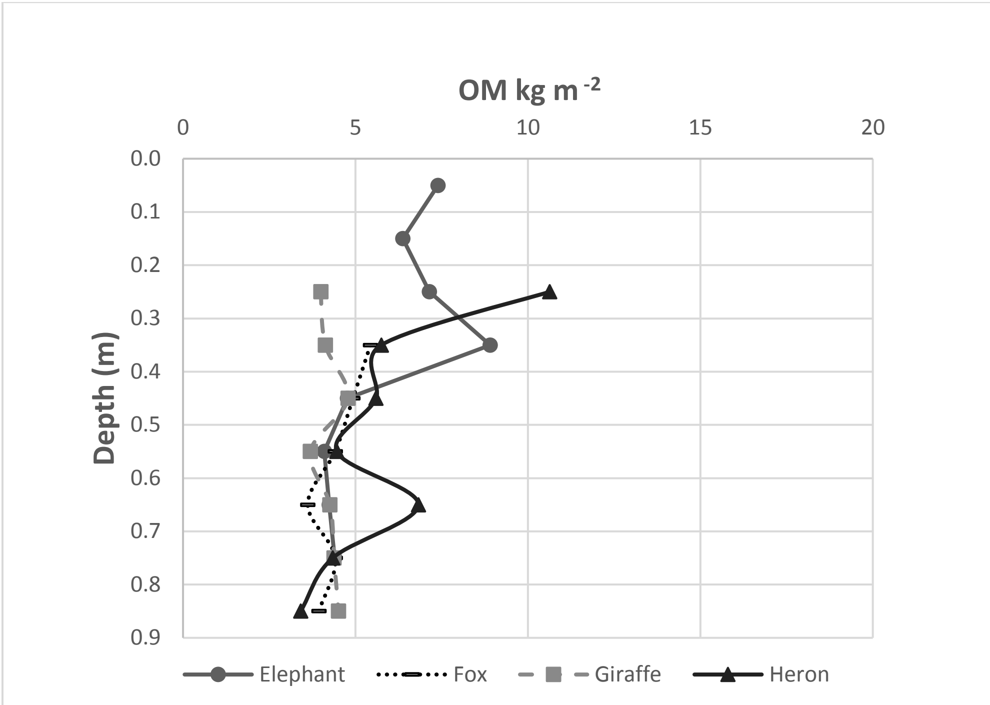

Figure 23. Soil OM kg m^{-2} by depth in the west trench, corrected for fine-fraction bulk density. Table 13 in Appendix C lists sample size used for averages at each 10 cm depth interval.

The variability in the relationship between depth and OM in the Heron grid is likely due to small sample size (only one value for depth intervals 0.70, 0.80, and 0.90 m). I had small sample sizes at these depths due to inability to collect bulk density on samples with high rock content.

The average weight of SOM in kg ha^{-1} per depth interval in each trench reflects the differences between the trenches in the top three horizons (Figure 24). Total weight of SOM in Mg is found by adding these average SOM kg m^{-2} values over the entire trench and multiplying these values by 10 (0.001 Mg=1 kg). The total Mg SOM ha^{-1} in the east trench is more than in the west trench. There were approximately 670 Mg SOM

ha^{-1} in the east trench and approximately 490 Mg SOM ha^{-1} in the west trench (Figure 24).

The SOC kg m^{-2} for each depth interval for each trench followed the same pattern as OM kg m^{-2} amounts (Figure 24). There is more SOC in the east trench than the west trench, as expected. The total SOC estimate was 322 Mg ha^{-1} from the east trench, and 200 Mg ha^{-1} from the west trench.

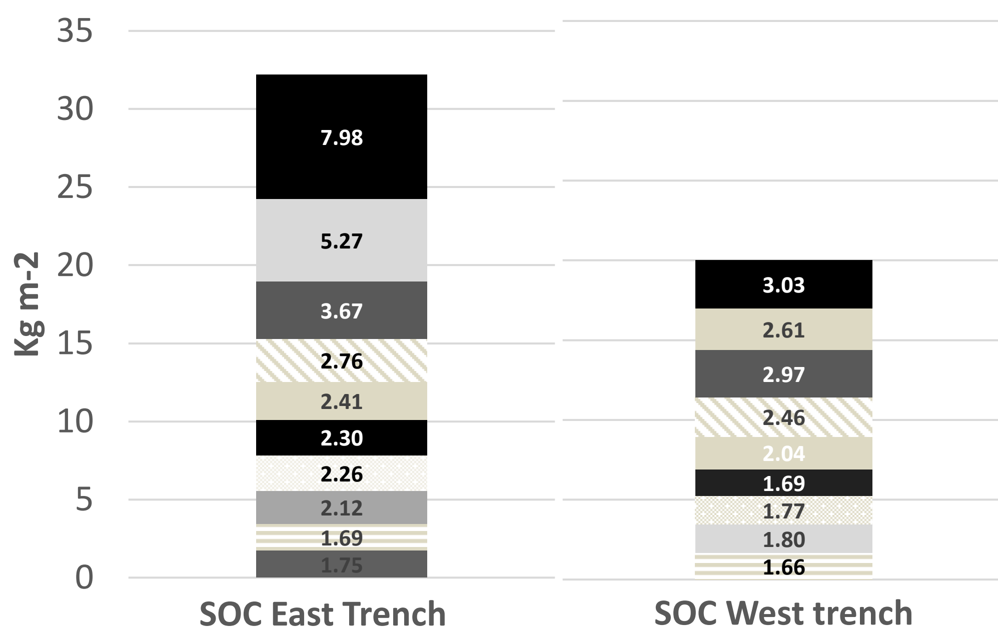

Figure 24. The average soil organic carbon (SOC) kg m^{-2} at each 10 cm depth interval for each trench. The thickness of the lines represents amount of SOC present. There are ten depth intervals in the east trench and nine depth intervals in the east trench, due to a rock layer. *n*= 300 for east trench and *n*= 174 in west trench. Table 14 in Appendix C lists sample size of each average.

SOM Sample Size

The suggested sample size needed to capture the same amount of variance that I found in OM % per 10 cm depth interval depended on the chosen margin of error (ME). Margin of error represents the percent of error in estimates. I chose the smallest margin of error (ME) resulting in a sample size between 1 and 20, with two exceptions (top depth interval in east trench and the second depth interval in west trench), where a higher ME or larger sample size must be used. This method resulted in a margin of error of 3.0 for depths of 0 to 20 cm, 0.70 for depths 20 to 40 cm, and 0.30 for depths 40 to 100 cm (Table 3). If I had used the same margin of error for all depths some of the suggested sample sizes would have been over one thousand.

Table 3. Needed sample size (*n*) for each depth interval for each trench compared with actual sample size taken. Margin of error

Depth (cm)	Margin of Error	Predicted *n* East trench	Actual *n* East trench	Predicted *n* West trench	Actual *n* West trench
0-10	3.0	**161**	*33*	**6**	*19*
10-20	3.0	**18**	*34*	**1**	*20*
20-30	0.70	**4**	*34*	**18**	*20*
30-40	0.70	**2**	*34*	**29**	*20*
40-50	0.30	**6**	*33*	**17**	*20*
50-60	0.30	**10**	*30*	**6**	*20*
60-70	0.30	**13**	*30*	**10**	*18*
70-80	0.30	**7**	*29*	**7**	*17*
80-90	0.30	**8**	*25*	**7**	*17*
90-100	0.30	**5**	*18*	**1**	*3*

DISCUSSION

SOC:SOM Ratios

It is widely accepted that SOM contains about half C by weight (Broadbent, 1953; Donkin, 1991; Jain et al., 1997). The standard 0.50 OC:OM ratio is often applied to organic components and a 0.58 ratio is usually applied to mineral soil (Gortner, 1916; Jain et al., 1997; König, 1911), but error can occur because these ratios depend on soil type, source of SOM and depth, and can vary significantly within the same soil horizon as well as seasonally (Ball, 1964; Donkin, 1991; Jain et al., 1997; Lunt, 1930; Nelson and Sommers, 1982). Better quantitative C estimates can be obtained by using separate SOC%:SOM % ratios for different vegetation, soil types, soil horizons, and organic components (Jain et al., 1997).

I refined the SOC:SOM ratio for this site according to depth in the soil profile My SOC:SOM ratios calculated using LOI OM % and OC % from combustion by the Oregon State University lab ranged from 0.20 to 0.97, with an average of 0.45. The 0.97 ratio was taken from an O horizon sample in the Centaur grid, but was not included in all analyses, because this ratio was most likely calculated in error. Most OC:OM ratios were within the range of 0.20 – 0.50. Even with a wide range of ratios, SOM continues to be a good predictor of SOC. The average ratio in the top two soil horizons (0-20 cm depth) was 0.41, and this ratio increased to an average of 0.49 in deeper soil horizons (20-100 cm depth). One explanation for this relatively low ratio (0.41 compared to 0.58 widely-

accepted), may be a higher proportion of fulvic acids present, which have lower C content, and are more common in forest soils.

Better quantitative C estimates can be found by using separate SOC:SOM ratios for different soil horizons, vegetation, soil types, and location. For example, if there was 100 Mg OM ha^{-1} calculated for a particular site and the traditional 0.58 ratio was used, the result would be 58 Mg C ha^{-1}. If instead the OC:OM ratio I found at 20 cm depth (0.41) was used, the result would be 41 Mg C ha^{-1}, and if the ratio I found for 20 –100 cm depths was used, the result would be 49 Mg C ha^{-1}. These differences of 9 to 17 Mg C ha^{-1} can make a large difference when extrapolating findings across a landscape or attributing them to management effects. Environmental factors such as vegetation, topography, hydrology, and previous management could be influencing the average low ratio (0.45) found. Additionally, the variability in C attributable to bulk density estimates may exceed the amount of soil C or SOM attributable to land use changes.

SOC decomposition is strongly reduced with depth in most soils (Carney et al., 2007; Cheng et al., 2003; Fontaine et al., 2004; Kuzyakov et al., 2000; Malosso et al. 2003). Surface layers are often dominated by younger fast-cycling (active) C, and subsurface layers are dominated by older slow-cycling (recalcitrant) C (Fontaine et al., 2007). Risk et al. (2008) found that SOC decomposition in surface soils was 100 times more active than soils at 35 cm depth, but placed under similar conditions in a laboratory, there were no significant differences in decomposition rates. These studies focused on grasslands that contain SOC from old forests, but these trends can be generalized to many

well-drained deep soils, because they are founded on a basic ecological function of fresh C coming from plant litter at the surface. Without fresh C inputs to stimulate microbial activity, the stability of C in deeper horizons is maintained. Soil microorganisms are able to decompose older SOC from deep horizons in a laboratory setting once fresh organic C is added (Fontaine et al., 2007). The higher OC:OM ratio with depth is reflected by the low rate of decomposition of recalcitrant SOC at depth. This lower decomposition rate is due to multiple factors that inhibit microbial activity including an increase in bulk density which decreases pore space and aeration, and the lack of fresh C stimulating microbial activity (Risk et al., 2008).

The increase of SOC:SOM with depth could also suggest a qualitative change in the SOM, since more C tends to remain when SOM originates from roots than from leaf litter, though this was outside the scope of my study. As depth increases, the source of SOM could transition from being litter-derived at the surface to being more root-derived. The complex nature of SOM helped guide methodology in taking large sample sizes and refining OC:OM ratios at this study site, without solely relying on previously-determined ratios. This information was developed to be useful in other regional C assessments.

SOM and Depth

Hypothesis 1 was supported by the decrease of OM % and OM kg ha^{-1} with depth in the soil profile support. However, approximately 51% of OM is found in the top 20 cm of my soil profiles. Forest Inventory Analysis (FIA) protocol typically only samples to

20 cm, as do many other soil science studies (Harrison et al., 2011). Future scientific studies should not neglect the lower 80 cm, due to almost half of the SOM in this forest residing there (Harrison, et al., 2003; Harrison et al., 2011). Compared with grassland soils, the greater acidity of forest soils can inhibit soil organisms from mixing surface litter into the mineral soil (Belsky, 1994). Thus, although forest soils typically store most of their organic matter in the forest floor (O horizon) and a thin A horizon, some SOM still occurs at greater depths (Harrison et al., 2011). In mature forest soil profiles, a leached soil horizon (E horizon) commonly exists due to the organic acid generated from OM decomposition and microbial activity (Risk et al., 2008). However, there is not an E horizon at my study site (Appendix A), as E horizons do not typically form in Humboldt County due to unstable landscapes, high amounts of SOM due to favorable climate for plant productivity, and relatively fine-textured soils. In contrast, E horizons tend to form in more coarse textured soils on flatter landscapes.

Soil aeration, the process of air circulating through the soil, decreases with depth and is related to many soil properties including D_b. Diffusion is determined by the soil's physical properties such as texture, structure, and especially pore size, which are all affected by OM (Neira et al., 2015). With less oxygen at depth due to slow rates of diffusion and relatively high production of CO_2 by respiration, there is an expected decline of OM with depth. The persistence of C with depth could be a result of it being bound to minerals and existing in a form that decomposers cannot access (Fontaine et al., 2007). Iron oxides play a role in the retention of SOC, and iron oxides were found at

depths of 90- 110 cm, but it is unlikely that the influence of these oxides is greater than the influence of low oxygen on SOC decomposition (Culman et al., 2012).

The depth trends between the two trenches were similar, as expected, with slight variations in the Elephant and Heron grids, which was likely a result of small sample sizes and/or lithologic discontinuity. My data suggest that SOM will decrease with depth, and given the same soil forming factors, soil structure, past management, and vegetation, depth is a valuable predictor for SOM (Lawrence et al., 2015).

SOM and Bulk Density

Bulk density and rock measurements are necessary to convert soil nutrient measurements to a mass per area basis, in order to compare areas with different bulk densities or to evaluate nutrient processes on site (McNabb et al., 1986). I had a wide range of bulk density values with a low of 1.04 and a high of 1.97 g cm $^{-3}$, though this highest value is thought to be calculated with error. Hypothesis 3 is supported by the decrease in OM % with the increase in D_b but the factors are not highly correlated. I expected a more linear decrease of OM % with higher D_b values, but there is a sharp increase in D_b values at depths of 0.40 m and 0.50 m.

One explanation of these findings is that D_b often increases with depth due to overburden (the weight of the above soil horizons) and compaction, which may be additionally increased at this site by logging operations that took place in the LWSDTF in the 1950s. D_b can increase with compaction from heavy loads or equipment, as soil particles rearrange closer together (Dickerson, 1976) resulting in decreased infiltration

ability (Johnson & Beschta 1980), decreased gas exchange (Steinbrenner, 1959), and an increase in resistance to penetration by roots (Forristall & Gessel, 1955). The type of forest soils at this study site (gravelly loam, gravelly clay loam, and silty clay loam) are often susceptible to compaction as they are loose, have moderate fine granular structure in the top horizons and are slightly sticky and friable (Froehlich et al., 1985; NRCS 2008). Given the topography and climate of the region lower aeration with depth was expected, and this absence of oxygen can change the nature of the decay process and affect nutrient cycling, thus affecting plant growth and SOM inputs and cycling (Huntington et al., 1989). In my study, OM % decreases with depth in the same way that D_b increases with depth. It is possible for D_b to increase even with constant SOM inputs due to compaction alone (Torn et al., 2009), but D_b is often higher in areas with smaller amounts of SOM because SOM has lower density than minerals.

This type of soil can also have high rock content, and although I used rock content when calculating D_b, it is difficult to take accurate D_b measurements in rocky forest soils (Harrison et al., 2003; Page-Dumroese et al., 1999). If rock presence was underestimated as part of D_b calculations, D_b estimates would be overestimated. Rock-fragment content was high in both trenches but more so in the west trench. In the west trench, the rock content increased considerably with depth, with the increase starting at 20-30 cm depth with approximately 5 cm^3 dm^{-3} of rocks, then increasing to approximately 17 cm^3 dm^{-3} at 80 – 90 cm depth. This rock layer could represent an unexpected layer of alluvial rocks at a depth of 0.60- 0.90 m in the west trench, which suggests lithologic discontinuity, and could represent a former creek bed before uplift

occurred. These alluvial rocks made it difficult to extract many intact aggregates from the profile at these depths, and it was difficult to draw solid conclusions from these lower depth intervals due to small sample sizes. If there was an error of +/- 0.5 g or 0.5 cm^3 in rock content calculations, then bulk density estimates could err by up to +/- 0.30 g cm^{-3}. Despite the meticulous lab work and calculations performed in this study, we have a large range of values and higher D_b values than expected.

These results could also be due to inherent errors with the coated clod method, which uses the air-dry volume of the soil, which is lower than the field-moist volume of the soil that other methods use, and can result in under estimation of D_b (Blake, 1965). This method often gives higher bulk density values than do other methods and does not take inter-clod spaces into account (Blake, 1965). It is possible that the especially high bulk density values can be attributed to large rock presence in some samples, and the inability to precisely measure rock volume and rock weight when using the coated clod method.

It is recommended that where rock fractions (> 2mm) are abundant, they should be included in soil C calculations (Page-Dumroese et al., 1999), and excluding these rock fractions can result in sampling bias and inaccurate measurements of SOC (Corti et al., 1998; Fernandez et al., 1993). There was increasing rock content with depth, especially in the west trench. However, it is very difficult to break down and grind rocks to powder for C analysis, and I was not able to do this analysis in this study. In the future, when the > 2 mm rocky fraction comprises a significant portion of the soil matrix, the contribution of these fractions to soil C should be considered (Harrison et al. 2003). The lack of rock

C content analysis could have resulted in underestimation of SOC estimates, but at this site rocks comprised < 5% of the soil matrix, so it is unlikely that C was grossly underestimated. With the variations in bulk density measurements, it is uncertain whether or not we can always attribute changes in soil C to land use changes, and should consider or reconsider the inherent fluctuations and errors in measurements when expanding estimates across an area.

SOM and Roots

We found an increase in OM % with root content, which supports hypothesis three, though the relationship is not as strongly correlated as expected. There is evidence that soil adjacent to roots in undisturbed temperate forest sites has larger C mineralization rates than in bulk soil (Phillips & Fahey, 2006), and although many factors contribute to soil C accumulation, root biomass is a primary factor (Koteen et al., 2015). I found higher average root content at 20- 30 cm depth in the east trench and in the west trench average root content peaked at 20 cm depth, though higher root content continued to 40-50 cm depth. Root biomass is sometimes highest in the surface to 40 cm depth near clusters of trees, while isolated trees tend to have a steeper reduction in soil C below 10 cm depth (Koteen et al., 2015).

My findings represent peaks of root biomass with depth in each trench, but only weakly correlate with the SOM found at these depths. Based on these findings and what is known of C cycling and root input, I expected to find stronger linear relationships between OM % and root content, but within a forested setting the results were

confounded by many samples having median values of SOM and median values of root content. It has been suggested that more than a 50 m aboveground gap needs to occur before there is a below ground gap in roots (Vogt et al., 1995). The proximity of the surrounding trees and their roots may have created overlapping root populations, with several primary or secondary “peaks” of root biomass. This horizontal consistency in root presence makes linear relationships less likely. It may be more useful to study several individual trees separately and measure SOM along a gradient (Vogt et al., 1995). The weak correlation may also be due to a few samples from 60-90 cm depth containing a rare large diameter root but low amounts of SOM. Conversely, some samples from top horizons had fresh litter with high SOM but no roots. There are other complicating factors such as increases in D_b which reduces root depth overall, and lack of large diameter roots in our sampling, due to placement of the trenches. Sample extraction took place immediately after trenches were opened, so it is unlikely that enough time passed to influence root, C, and soil moisture dynamics.

Soil C is generally highest in the top 10 cm of the soil profile, and remains high from 10 cm to 20 cm depth (Harrison et al., 2011), especially when this corresponds with being 2 to 4 m from a tree bole, which suggests a second peak in roots with distance from tree bole. In temperate forests, soil C has been found to retain root-derived C longer than C derived from leaf litter, and although we did not test the source of the SOM found at depths, it is possibly derived from roots (Bird et al., 2008).

My root extraction method (NRCS, n.d.) did not allow for 100% of roots to be extracted, and a different method of root extraction may have resulted in a stronger

correlation of SOM and roots. There is no consensus on which methods are best for accurately estimating root biomass (Addo-Danso et al., 2015). Based on personal lab observations and according to Koteen and Baldocchi (2013), there are diminishing returns with additional time and effort (30-40 min) spent on extracting an additional 0.01 g of fine roots. A more intense extraction method was not possible for the large sample sizes I had. I used a 1 mm mesh sieve for fine roots, but other studies using a 0.25 mm mesh sieve found higher amounts of root biomass and significant correlation between SOM and root presence (Amado & Pardo, 1994; Livesley et al., 1999). However, these studies analyzed savanna ecosystems, and this difference in study setting may account for the difference in results.

When we tested root samples for OC:OM ratio, we found an average root OC: OM ratio of 0.49. The commonly accepted C content of woody materials including stems, branches, and roots is 48- 50 % of their mass (Gortner, 1916; Jain et al., 1997; König, 1911). The widely-accepted OC:OM ratio in roots and woody materials is 0.48 (Nelson & Sommers, 1982), which is supported by my findings.

SOM and Distance to Tree Bole

I found an increase in SOM with distance from tree bole, which does not support hypothesis four, and is instead contradictory of the relationship expected. In oak savannas, the greatest accumulation of C has been found a few meters from the bole of older trees, but for younger trees the greatest amount of C is found right next to the bole

in oak (Koteen et al., 2015; Longdoz et al., 2016). These patterns are likely related to root growth, and may influence SOM amounts and distribution (Vogt et al. 1995).

It is unlikely that SOM truly increases with distance from tree bole, given that more litter accumulates under tree canopy, root densities are higher near tree bole, and both of these contribute to microbial activity which is another factor, though outside the scope of this project, that is known to influence SOM. It is possible that the relationship I found was confounded by the forested setting of the study site, and the methods used to incorporate tree distance into my study. Although I chose trench sites carefully according to investigative parameters and ability to represent of LWSDTF soils, the forested setting of my study site may have confounded our results. With many trees contributing to SOM and SOC in a forested setting, the distance to an individual tree or the average distance to trees may not affect SOM as much as predicted. All studies do not agree on the distribution of soil C and its relationship to distance from trees in a forest setting, with some studies suggesting that soil C may be stored in fast to medium turnover pools, with more soil C being present in areas closer to trees with higher root density (Ceulemans et al., 1999; Vogt et al., 1995). Other studies suggest that SOC is stored in long-term pools, deeper than most roots are found (Lawrence et al., 2015). However, when considering longer-term soil C, trees and their roots operate on much shorter time scales than soil C (Epron et al., 2012). Results may be different at a site where comparisons between presence and absence of tree roots could be compared along a gradient, or in a site where trees have been removed, with SOC being tracked across time.

Even though my method of averaging and indexing trees has been used previously (Slack et al., 2016), this method may have led to inaccurate results. By indexing and averaging each tree in both trenches, the data may have been distorted in a way that did not draw distinctions between individual tree distance, distance from clusters of trees and their possible effects on SOM amounts. This may have been a good method to analyze unwieldy data, but may have clouded the relationships, if any, between SOM amounts and distance from tree bole. Future studies may find more strongly correlated results by looking at areas where forests neighbor savannas (Belsky, 1994). Compared to more pronounced gradients in forest savanna settings, mixed conifer forests may not show strong relationships between SOM and distance to tree bole due to closed canopies and spatial averaging of inputs over time.

Statistical Models

I depicted individual predictor variables in relation to SOM and depth, and additionally built a Generalized Linear Mixed Model (GLMM). The dataset for the GLMM consisted of 187 soil samples that had data for all predictor variables. When looking at each predictor individually with depth functions and regressions, I had higher sample sizes due to larger subsets of data. Looking at predictor variables individually also enables us to depict depth functions and overall inventory more accurately.

The top generalized linear mixed model (GLMM) for OM % was the full model, which included bulk density (D_b), depth interval (depth), amount of roots present (roots), average distance to tree boles (distance), and horizontal position within the trench as

random variable. Based on the standardized coefficients, depth had the strongest association with OM %, followed by bulk density, roots, and distance.

The top model includes distance, which was surprising due to the contradictory findings of what is widely-accepted in regards to relationships between SOM and tree bole. AIC scores penalize models for increased of predictors, therefore inherently choosing the most parsimonious model. The interaction term D_b:Depth would have explained more variance in the model and there is an obvious relationship between the two variables, but they were excluded due to variance inflation, indicated by a Variance Inflation factor (VIF) of more than 10.

When calculating for model accuracy, the results showed that our model could predict SOM % within 1.34 %, when considering depth, D_b, roots, distance from tree bole, and location as random variable. When studying SOC and SOM processes over time, the scale of analysis and dominant factors can change from a millennial scale compared to an hourly scale (Torn et al., 2009), but the relationships between SOM and depth, D_b, roots, and distance from tree bole can be useful for measuring soil C in the coming decades.

Total SOM and SOC Inventory

My baseline inventory of SOM and SOC at this study site was created in order to capture a snapshot in time at the LWSDTF. It may be used in future studies to track changes over time at this study site, with potential to inform SOM and SOC dynamics on

a regional scale. The total inventory was 670 Mg SOM ha^{-1} in the east trench and 490 Mg SOM ha^{-1} in the west trench. Using my refined OC:OM ratios for the different soil depth intervals, I calculated 322 Mg SOC ha^{-1} for the east trench and 200 Mg SOC ha^{-1} for the west trench. These values represent a large potential of C storage and are close to what I expected for soil C in this forest. The east trench was sampled to a depth of 1 m and the west trench was sampled to 90 cm due to a prohibitive rock layer. However, this difference in sampling depth only accounted for higher amounts of SOM and SOC in the east trench by 42.6 Mg SOM ha^{-1} and 17.5 Mg SOC ha^{-1}.

In south-central Washington, 20-year-old, 40-year-old, and 60-year-old Douglas-fir forests were found to have 157 Mg SOC ha^{-1}, 175 Mg SOC ha^{-1}, and 154 Mg SOC ha^{-1} in the top 20 cm, respectively (Klopatek, 2002). The Washington study only sampled to a depth of 20 cm, and the corresponding SOC amounts to 20 cm depth in my study were 133 Mg SOC ha^{-1} in the east trench and 56 Mg SOC ha^{-1} in the west trench. My estimates are within the expected range, though the west trench is low in the top two horizons. The variation could be attributed to differences in climate, topography, and parent material. As discussed previously, D_b values, which are used to calculate SOC or SOM over a given area, can range widely depending on methods and soil type. The Washington study looked at organic-rich Andisols, which have a relatively low bulk density range (0.70 to 0.92 g cm^{-3}), compared to 1.04 – 1.72 g cm^{-3} found at my study site, excluding the highest value, thought to be calculated in error (Klopatek, 2002). In addition, Redwood National Park (RNP) recently conducted a soil survey in which a range of SOC Mg ha^{-1} values was found, from a low of 11 Mg SOC ha^{-1} in floodplain

soils with very little vegetation to a high of 468 Mg SOC ha^{-1} in an old-growth redwood forest with thick herbaceous understory (van Mantgem et al., 2013). The average found across a variety of study sites at RNP was 213 Mg SOC ha^{-1}, which is nested within the range found between trenches and is close to our average of 261 Mg SOC ha^{-1}. The RNP findings may be a better comparison due to similarities in sampling depth (1 m or more at RNP), and stronger similarities in climate with my site, since both my study site and RNP are influenced by the coastal climate of Northern California.

The differences between trenches are most likely due to the landscape position of each trench, as previously mentioned. There is variation in SOM and SOC between the two trenches in the top 30 cm, but there is little to no difference in amounts of SOM deeper than 30 cm. When comparing average kg SOM ha^{-1} in each trench per depth interval, the east trench had 55 % more in the 0-10 cm horizon, 41 % more in the 10-20 cm horizon, and only 3 % more in the 20-30 cm horizon. These findings indicate that the differences between trenches are mainly a result of differing litter input amount and/or surface accumulation, which is likely a result of trench position in the landscape.

The east trench was located at the toe slope in a position of accumulation, and litter input and accumulation and input was higher at this location. The west trench was located at the edge of a convex shoulder with approximately 30 % slope with a north aspect, and adjacent to a concave bowl-shape feature. This concave hill slope adjacent to the west trench had an area of accumulation at its base, possibly deposited from the amount of litter that would have contributed to the OM in the west trench. Instead of disregarding the variation we see at one study site, this difference in estimates can

highlight the variability in SOM and SOC across a landscape and even within one study site. When we calculate SOM and SOC on a regional scale, slope and landscape position should be taken into account as equally important variables as other environmental factors. To further improve C quantification, future studies should sample from a variety of landscape positions within a site, such as from a ridge top where there the least amount of litter input and SOM would be expected, and also from the base of any convex slopes present.

Sample Sizes

I calculated suggested samples sizes needed to capture the same amount of variance in SOM found at 1 m depth. I calculated these sample sizes using different margins of error (ME) according to variance found at each depth interval. Future studies can take smaller sample sizes to capture the same amount of variance I found, which is useful when trying to assess a site efficiently, and each soil sample taken represents time and money spent. The large predicted sample size (161) found for the top horizon (0- 10 cm) in the east trench is due to a high standard deviation of 19.4. This is due to high OM % in this horizon as a result of fresh litter.

CONCLUSION

Mechanisms of SOM are not easily generalized within temperate biomes, and more complicated relationships exist between contributing factors and processes. Soil organic matter distribution at this site is likely due to influences of vegetation, topography, and hydrology, affecting the SOM variability on a landscape level (Torn et al., 2009). I refined the OC:OM ratio for soils at this site, in order to more accurately quantify soil C amounts for this study and future studies. Despite the range in ratios found, SOM continues to be a good predictor of SOC.

I analyzed relationships between SOM and depth, bulk density, roots, and distance from tree bole individually and collectively. My hypotheses were supported by (1) a decrease in SOM with depth, (2) a decrease in SOM with bulk density, and (3) an increase in SOM with root content. However, our hypothesis (4) that SOM would decrease with further distance from tree bole, was not supported. All four factors were significant predictors in SOM when tested in a GLMM.

Forest soil C pools are difficult to estimate quantitatively due to difficulties in measuring C directly and the high variation in soil properties often found in rocky forest soils (Huntington et al., 1989; Harrison et al., 2011). I created a baseline inventory of SOM and SOC for my study site, finding SOM estimates of 670 – 490 Mg SOM ha^{-1} and SOC estimates of 322 – 200 Mg SOC ha^{-1}, from the east and west trenches respectively. These findings may be used for long-term monitoring of SOM spatial patterns and amounts, as land use and forest management changes temporally. Small changes in SOM

storage rates can be difficult to detect, even with very intensive sampling, due to time since treatment, overburden pressure at lower depths, and intensity of harvest removals changing over time (Yanai et al., 2000).

I calculated suggested sample sizes needed to conduct a study similar to this one, with emphasis on reducing sampling intensity in order for studies to increase affordability. I hope future studies will use a similar sampling design and my calculated suggested sample sizes to track changes in SOM and SOC.

Land use change can influence SOC, especially when a forest is converted for agricultural purposes, and may deplete SOC stock by 20-50% (Schlesinger, 1985; Post & Mann, 1990; Davidson & Ackerman, 1993). Previous studies show that grasslands store less total C than forested areas but a higher proportion of C in grasslands is stored as soil C (Kirby & Potvin, 2007). Other studies suggest that post-harvest rates of mineralization increase beyond the rates of litter input in the soil profile (Diochon & Kellman, 2008). These increased rates of mineralization can lower C concentrations for 15 years after timber harvesting, and C concentration does not begin to increase again until 45 years post-harvest (Diochon & Kellman, 2008). Any management change that affects standing biomass like thinning, fertilization, or genetic improvement, can also change the amount of CO_2 photosynthesized by the forest (Harrison et al., 2011). However, there may also be a smaller amount of variability attributable to land use than can be found in nature, depending on sampling methods. For example, increased atmospheric CO_2 may or may not affect our forests in the ways which have been predicted; trees may focus more C in aboveground biomass and may allocate less C to the root system (Epron et al., 2012). If C

storage is a goal for the LWSDTF, there is a large potential to store soil C if managed properly. Since even active soil C changes on longer-term scales, it is important to establish a baseline inventory at present to track the future potential effects of variable density thinning and climate change on soil C at LWSDTF, and I hope this study influences future land use decisions at LWSDTF and in the northern California region.

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APPENDIX A: PEDON DESCRIPTIONS

Table 4. Modal pedon description, official description, of Mooncreek series in an area typically under Douglas-fir, tanoak, Pacific madrone, and salal. (NRCS, 2008).

Horizon	Depth (cm)	Color/Texture	Structure	Roots	Pores	Rocks	pH
O	0 - 4	Very dark gray (10YR 3/1), slightly decomposed Douglas-fir and tanoak needles and leaves, black (10YR 2/1) moist	Loose, nonsticky and nonplastic	Common very fine roots	Common fine irregular pores		Moderately acid, pH 5.6
A	4 - 8	Brown (7.5YR 5/4) gravelly loam, dark brown (7.5YR 3/4) moist	Moderate fine granular structure; slightly hard, very friable, slightly sticky, slightly plastic	Many very fine to medium roots	Many very fine and fine tubular; many medium interstitial pores	18 % gravel	Very strongly acid, pH 4.7
ABt	8-16	Brown (7.5YR 5/4) gravelly loam, dark brown (7.5YR 3/4) moist; few faint clay films on all faces of peds	Moderate fine subangular blocky structure; slightly hard, very friable, moderately sticky and moderately plastic	Many very fine to medium roots	Many fine and medium and common coarse tubular pores	18 % gravel	Very strongly acid, pH 5.0

Horizon	Depth (cm)	Color/Texture	Structure	Roots	Pores	Rocks	pH
Bt1	16-54	Yellowish brown (10YR 5/4) gravelly clay loam, dark yellowish brown (10YR 4/4) moist; few distinct clay films	Strong fine and medium subangular blocky structure; slightly hard, friable, moderately sticky and moderately plastic	Many fine and medium and common coarse roots	Many fine and medium and common coarse tubular pores	18 % gravel	Extremely acid, pH 4.4
Bt2	54-96	Yellowish brown (10YR 5/4) gravelly silty clay loam, dark yellowish brown (10YR 4/6) moist; common distinct clay films	Moderate fine and medium angular blocky structure; slightly hard, friable, moderately sticky and moderately plastic	Many fine and medium and common coarse roots	Many fine and medium tubular pores	20 % gravel	Extremely acid, pH 4.4
Bt3	96-139	Yellowish brown (10YR 5/4) gravelly silty clay loam, dark yellowish brown (10YR 4/6) moist; common fine very weakly cemented iron-manganese masses, strong brown (7.5YR 5/6) moist; common distinct clay films	Moderate fine and medium angular blocky structure; hard, firm, very sticky and very plastic;	Common medium and coarse roots	Common fine and medium tubular pores	18 % gravel	Very strongly acid, pH 5.0

Horizon	Depth (cm)	Color/Texture	Structure	Roots	Pores	Rocks	pH
Bt4	139-200	Light yellowish brown (10YR 6/4); gravelly silty clay loam, yellowish brown (10YR 5/6) moist; common fine very weakly cemented iron-manganese masses, strong brown (7.5YR 5/6) moist; common distinct clay films	Moderate medium and moderate fine subangular blocky structure; hard, firm, very sticky and very plastic	Common medium and common coarse roots;	Common medium tubular pores	16 % gravel	Very strongly acid, pH 4.5

Table 5. East Trench Pedon description by Greg Davis. Coarse roots defined as >2 mm diameter and fine roots < 2 mm diameter. This description has not been correlated with the official Mooncreek series description.

Horizon	Depth (cm)	Color/description	Texture	Roots	pH
O	0-5	Fresh litter to partially decomposed material, semi-compacted by past foot traffic			NA
A	5-23	Light yellowish brown (10 YR 6/4), dark brown (10 YR 3/3) moist	Loam, strong fine to coarse granular structure; friable, sticky and plastic	common very fine to medium roots	5.6
Bt1	23-42	Light yellowish brown (10YR 6/4), dark yellowish brown (10YR 3/4) moist	clay loam, strong fine granular to coarse sub-angular blocky structure; friable, sticky and plastic	common very fine to medium roots;	5.6
Bt2	42-65	light yellowish brown (10YR 6/4), dark yellowish brown (10YR 3/4) moist	silty clay, strong medium to coarse sub-angular blocky structure; very friable and very sticky,	common very fine to medium roots;	5.6
Bt3	65-91	light yellowish brown (10YR 6/4), olive brown (2.5Y 4/4) moist	silty clay, strong medium to very coarse sub-angular blocky structure very friable and very sticky	few fine roots; strong acid	5.2

Horizon	Depth (cm)	Color/description	Texture	Roots	pH
Bt4	91-110	light yellowish brown (10YR 6/4); olive brown (2.5Y 4/4) moist; some strong brown (7.5YR 5/4) irregular iron concentrations	silty clay, strong medium to very coarse sub-angular blocky structure; very friable and very sticky	very few very fine roots	5.2

Table 6. West Trench Pedon description by Malia Ortiz. Coarse roots defined as >2 mm diameter and fine roots < 2 mm diameter. This description has not been correlated with the official Mooncreek series description.

Horizon	Depth (cm)	Color/description	Texture	Roots	pH
O	0-5	Fresh litter to initially decomposed material, semi-compacted, Douglas-fir, grand fir, fern, and tanoak			NA
A1	5-13	dark grayish brown (10YR 3/2), moist	silt loam (29-66-6), medium coarse sub-angular blocky structure	many medium and fine roots.	NA
A2	13-34	brown (10YR 4/3) moist,	silt loam (34-55-11), medium coarse sub-angular blocky structure	many medium roots, few fine roots	NA
Bt1	34-57	dark yellowish brown (10YR 4/4) moist	skeletal silt loam (36-50-14), very coarse sub-angular blocky structure, clay films present (10%).	few coarse roots and few fine roots	NA
Bt2	57-85	dark yellowish brown (10YR 4/4) moist, few coarse root, clay films present (20%).	skeletal silt loam (32-55- 10), coarse sub-angular blocky structure	few fine roots	NA

Horizon	Depth (cm)	Color/description	Texture	Roots	pH
2C	67-160	grayish yellowish brown (10YR 4/2) moist.	skeletal silt loam (36-55-9), massive structure	few very coarse roots, few medium roots	NA

APPENDIX B: VEGETATION SAMPLING

Table 7. Trees within 10 m of the east trench including species and diameter at breast height (DBH) of each tree. Tree species present include Grand fir (*Abies grandis)*, Douglas-fir *(Pseudotsuga menziesii)*, and tanoak (*Notholithocarpus densiflorus)*.

East trench trees	Species	DBH (cm)
Tree 1	*Abies grandis*	36
Tree 2	*Abies grandis*	38
Tree 3	*Notholithocarpus densiflorus*	33
Tree 4	*Notholithocarpus densiflorus*	44
Tree 5	*Abies grandis*	59
Tree 6	*Abies grandis*	23
Tree 7	*Abies grandis*	55
Tree 8	*Pseudotsuga menziesii*	59
Tree 9	*Pseudotsuga menziesii*	53
Tree 10	*Abies grandis*	88
Tree 11	*Abies grandis*	40

Table 8. Trees within 10 m of the west trench including species and diameter at breast height (DBH) of each tree. Tree species present include Grand fir (*Abies grandis),* Douglas-fir *(Pseudotsuga menziesii),* tanoak (*Notholithocarpus densiflorus),* and California bay (*Umbellularia californica*).

West trench trees	Species	DBH (cm)/ number of stems	DBH (cm)of multiple stems
Tree 1	*Pseudotsuga menziesii*	49	
Tree 2	*Abies grandis*	52	
Tree 3	*Abies grandis*	37	
Tree 4	*Umbellularia californica*	8 stems	19, 7, 10, 23, 18, 21, 16, 18
Tree 5	*Abies grandis*	60, old stump	
Tree 6	*Pseudotsuga menziesii*	61	
Tree 7	*Umbellularia californica*	5 stems	30, 35, 22, 16, 17,
Tree 8	*Umbellularia californica*	3 stems	24, 25, 29
Tree 9	*Umbellularia californica*	26	
Tree 10	*Umbellularia californica*	55	
Tree 11	*Umbellularia californica*	5 stems	26, 15, 25, 34, 24
Tree 12	*Umbellularia californica*	27	
Tree 13	*Umbellularia californica*	33	
Tree 14	*Umbellularia californica*	3 stems	27, 23, 15
Tree 15	*Umbellularia californica*	15	
Tree 16	Unknown	42, Old stump	
Tree 17	*Pseudotsuga menziesii*	30, Old stump	
Tree 18	*Pseudotsuga menziesii*	95	
Tree 19	*Abies grandis*	52	

West trench trees	**Species**	**DBH (cm)/ number of stems**	**DBH (cm)of multiple stems**
Tree 20	*Pseudotsuga menziesii*	41	
Tree 21	*Pseudotsuga menziesii*	37	
Tree 22	*Pseudotsuga menziesii*	63	

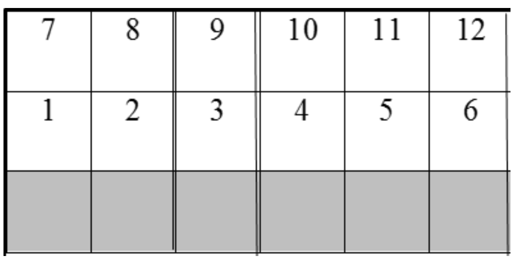

Figure 25. Vegetation sampling design for east trench. Shaded area represents trench location. Data were taken on south/uphill side of trench. Each numbered square represents one m^2.

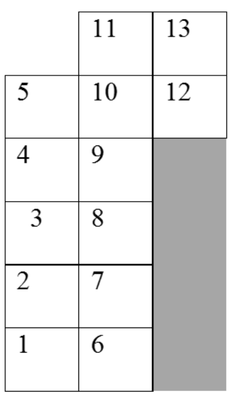

Figure 26. Vegetation sampling design for west trench. Shaded area represents trench location. Data were taken on east and south sides of trench. Each numbered square represents one m^2.

Table 9. Description of vegetation in each m^2 sampling grid for the east trench.

Square	Species	Diameter (cm)/ number of stems	Distance from trench face (cm)	Cover (%)
1	*Trientalis latifolia*	na	na	10
	Lilium columbianum	2 stems	21 cm	1
2	*Trientalis latifolia*	na	na	5
	Lilium columbianum	2 stems	50	2
	Notholithocarpus densiflorus (stump)	na	na	30
3	*Notholithocarpus densiflorus (stump)*	1st stump:12 2nd stump: 16	97	90
4	*Notholithocarpus densiflorus (stump)*	na	na	30
	Lilium columbianum	11 stems	na	20
	Trientalis latifolia	< 2 mm	32 cm	1
	Polystichum munitum	15 stems	56	10
5	*Polystichum munitum*	12 stems	90 cm	40
	Lilium columbianum	3 stems	15 cm	10
	Trientalis latifolia	10 stems		5
	Galium aparine	na	20 cm	5
	Toxicodendron diversilobum	na	10 cm	1
	Rubus ursinus	na	50 cm	5
6	*Rubus ursinus*	na	80 cm	5
	Toxicodendron diversilobum	na	75 cm	5

Square	Species	Diameter (cm)/ number of stems	Distance from trench face (cm)	Cover (%)
	Galium aparine	na	25 cm	1
	Iris douglasiana	na	10 cm	1
	Gaultheria shallon	3 stems	30 cm	10
7	*Lilium columbianum*	na	na	2
	Polystichum munitum	12 stems	181 cm	45
8	*No vegetation*			
9	*No vegetation*			
10	*Polystichum munitum*	2 stems		25
	Trientalis latifolia	3 stems		5
11	*Polystichum munitum*	2 stems	166 cm	25
	Trientalis latifolia	2 stems		5
12	*No vegetation*			

Table 10. Description of vegetation in each m^2 sampling grid for the west trench.

Square	species	Number of stems	Distance (cm)	Cover (%)
1	*Polystichum munitum*	7	15	15
2	*Polystichum munitum*	20	20	30
3	*Polystichum munitum*	9	40	20
4	*Polystichum munitum*	10	20 and 80	25
5	*Polystichum munitum*	19	60	50

Square	**species**	**Number of stems**	**Distance (cm)**	**Cover (%)**
6	*Polystichum munitum*	13	10 and 90	25
7	*Polystichum munitum*	10	90	15
8	*Polystichum munitum*	5	80	10
9	*Polystichum munitum*	4	25	10
10	*Polystichum munitum*	7	45	40
11	*Polystichum munitum*	10	50	5
	Oxalis oregona		95	20
12	*Polystichum munitum*	10	75	50
13	*Polystichum munitum*	3	60	5
	Lilium columbianum		40	5
14	*Polystichum munitum*	5	60	20

APPENDIX C: SAMPLING INTENSITY FOR BULK DENSITY AND ORGANIC MATTER

Table 11. Number of full volume (dm^3) and partial volume samples taken from each grid by depth interval. NA indicates that no sample was taken.

Depth (m)	Antelope *n*		Bison *n*		Centaur *n*		Dinosaur *n*		Elephant *n*		Fox *n*		Giraffe *n*		Heron *n*	
	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume	Full volume	Partial volume
0.05	4	NA	5	4	5	5	5	5	5	NA	4	NA	5	NA	5	NA
0.15	4	NA	5	5	5	5	5	5	5	NA	5	NA	5	NA	5	NA
0.25	4	NA	5	5	5	5	5	5	5	NA	5	NA	5	NA	5	NA
0.35	4	NA	5	5	5	5	5	5	5	NA	5	NA	5	NA	5	NA
0.45	3	NA	5	5	5	5	5	5	5	NA	5	NA	5	NA	5	NA
0.55	NA	NA	5	5	5	5	5	5	5	NA	5	NA	5	NA	5	NA
0.65	NA	NA	5	5	5	5	5	5	3	NA	5	NA	5	NA	5	NA
0.75	NA	NA	5	5	5	5	5	4	2	NA	5	NA	5	NA	5	NA
0.85	NA	NA	5	5	4	4	4	3	2	NA	5	NA	5	NA	5	NA
0.95	NA	NA	5	5	3	2	2	1	3	NA	0	NA	NA	NA	NA	NA

$$\textit{Equation 6.} \quad \textit{Bulk density calculations}$$

$$rock\ adjusted\ bulk\ density, D_b = \frac{(weight\ of\ uncoated\ clod\ in\ air - \text{rock weight})}{(volume\ of\ \text{uncoated}\ clod) - (rock\ volume)}$$

$$(Volume\ of\ uncoated\ clod = volume\ of\ coated\ clod - volume\ of\ parafin\ wax)$$

$$(Volume\ of\ wax = \frac{(weight\ of\ coated\ clod\ in\ air - weight\ of\ umcoated\ clod\ in\ air)}{0.9})$$

Note: rock volume was estimated from a similar size clod

Table 12. Number of samples used to find average OM% at each 10 cm depth interval in each grid. NA indicates that no sample was taken, due to inaccessibility or thick rock layer.

Depth (m)	Antelope *n*	Bison *n*	Centaur *n*	Dinosaur *n*	Elephant *n*	Fox *n*	Giraffe *n*	Heron *n*
0.05	4	9	10	10	5	4	5	5
0.15	4	10	10	10	5	5	5	5
0.25	4	10	10	10	5	5	5	5
0.35	4	10	10	10	5	5	5	5
0.45	3	10	10	10	5	5	5	5
0.55	NA	10	10	10	5	5	5	5
0.65	NA	10	10	10	3	5	5	5
0.75	NA	10	10	9	2	5	5	5
0.85	NA	10	10	7	2	5	5	5
0.95	NA	10	10	3	3	NA	NA	NA

Table 13. Number of samples used to find average OM kg m^{-2} at each 10 cm depth interval in both trenches. NA indicates samples in which kg m^{-2} could not be calculated because bulk density could not be measured due to lack of intact clods.

Depth	Antelope *n*	Bison *n*	Centaur	Dinosaur *n*	Elephant *n*	Fox *n*	Giraffe *n*	Heron *n*
0.05	2	NA	NA	NA	1	NA	NA	NA
0.15	3	NA	2	2	1	NA	NA	NA
0.25	3	4	2	4	3	NA	2	2
0.35	4	4	4	5	3	3	3	5
0.45	3	4	4	5	4	4	4	3
0.55	NA	3	5	4	3	2	3	2
0.65	NA	3	5	5	2	3	3	1
0.75	NA	4	5	5	1	3	3	1
0.85	NA	2	4	4	NA	3	2	1
0.95	NA	3	4	5	NA	NA	NA	NA

Table 14. Number of samples per horizon used for average OM kg ha^{-1}. The east trench has ten depth intervals and the west trench has nine depth intervals due to a rock layer. NA indicates depth intervals in which kg m^{-2} could not be calculated due to lack of bulk density measurements.

Depth midpoint (m)	East trench *n*	West trench *n*
0.05	2	1
0.15	7	1
0.25	13	7
0.35	17	14
0.45	16	15
0.55	12	10
0.65	13	9
0.75	14	8
0.85	10	6
0.95	12	NA

Table 15. Number of samples per 10 cm depth interval used to find average dried root weight (g) for each trench.

Depth midpoint (m)	East trench *n*	West trench *n*
0.05	17	10
0.15	15	13
0.25	15	12
0.35	19	12
0.45	11	12
0.55	10	9
0.65	6	9
0.75	8	9
0.85	5	12
0.95	7	1

APPENDIX D: VEGETATION LIST

Table 16. Vegetation list for L.W. Schatz Demonstration Tree Farm. Courtesy of Humboldt State University.

Native Trees

Common Name	**Scientific Name**
Grand fir	*Abies grandis*
Bigleaf maple	*Acer macrophyllum*
Red alder	*Alnus rubra*
Pacific madrone	*Arbutus menziesii*
Tan-oak	*Notholithocarpus densiflorus*
Oregon ash	*Fraxinus latifolia*
Douglas-fir	*Pseudotsuga menziesii*
Cascara buckthorn	*Rhamnus purshiana*
Willow	*Salix* ssp.
Western hemlock	*Tsuga heterophylla*
California bay	*Umbellularia californica*

Understory Plants

Common Name	**Scientific Name**
Oregon grape	*Berberis nervosa*
Blueblossom	*Ceanothus thyrsiflorus*
Creek dogwood	*Cornus stolonifera* var. *occidentalis*
California hazel	*Corylus cornuta* var. *californica*
Salal	*Gaultheria shallon*
Oceanspray	*Holodiscus discolor*
Osoberry	*Oemleria cerasiformis*
Mockorange	*Philadelphus lewisii*
Gooseberry	*Ribes uva-crispa*
Wood rose	*Rosa gymnocarpa*
Himalayan blackberry	*Rubus armeniacus*
Thimbleberry	*Rubus parviflorus*
Salmonberry	*Rubus spectabilis*
California blackberry	*Rubus ursinus*

Poison-oak	*Toxicodendron diversilobum*
Evergreen huckleberry	*Vaccinium ovatum*
Red huckleberry	*Vaccinnium parvifolium*

Non-Native Trees

Common Name	***Scientific Name***
Ponderosa pine	*Pinus ponderosa*
Monterey pine	*Pinus radiata*
Scotts pine	*Pinus sylvestris*
Giant sequoia	*Sequoiadendron giganteum*
Coast redwood	*Sequoia sempervirens*

Herbaceous Plants

Common Name	**Scientific Name**
Deer fern	*Blechnum spicant*
Bull thistle	*Cirsium vulgare*
Andrew's clintonia	*Clintonia andrewsiana*
Bedstraw	*Galium aparine*
Douglas iris	*Iris douglasiana*
Columbia lily	*Lilium columbianum*
Birdfoot trefoil	*Lotus corniculatus*
Brackenfern	*Pteridium aquilinum*
Buttercup	*Ranunculus californicus*
Hedge nettle	*Stachys palustris*
Coast trillium	*Trillium ovatum*
Northern maidenhair	*Adiantum pedatum*
Lady fern	*Athyrium felix-femina*
Fire-cracker flower	*Dichelostemma ida-maia*
Oxeye daisy	*Chrysanthemum leucanthemum*
Horsetail	*Equisetum* sp.
Honeysuckle	*Lonicera* sp.
Miner's lettuce	*Montia perfoliata*
Fetid adder's tongue	*Scoliopus bigelovii*
False Solomon's seal	*Smilacina stellata*
Pacific starflower	*Trientalis latifolia*
Western wild ginger	*Asarum caudatum*

Western bleeding heart	*Dicentra formosa*
Wild cucumber	*Echinocystis lobata*
Scouring rush	*Equisetum* sp.
Strawberry	*Fragaria virginiana*
Siberian candyflower	*Montia siberica*
Skunkweed	*Navarretia squarrosa*
Redwood sorrel	*Oxalis oregona*
Western sword fern	*Polystichum munitum*
Stinging nettle	*Urtica dioica*
Water speedwell	*Veronica anagallis-aquatica.*