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Effect of Surface Rock Fragment Cover on Accumulation of Organic Matter and Charcoal on Mountain Soils in Northern California

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by

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ABSTRACT OF THE THESIS

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Soil surface covers are critical to understanding the influence of aboveground inputs to underlying soils. Surface covers are often composed of organic material, but mountain soil surfaces are sometimes covered with rock fragments. This study compared mountain soils at two study sites in Klamath National Forest to determine the influence of surface rock fragments on physical soil properties and organic matter accumulation. One soil had a distinct surface rock fragment layer of cobbles and stones above the soil, and the other had only a layer of organic litter. Soil temperature and moisture were measured continuously for a year. Organic litter, soil organic carbon, and pyrogenic carbon were measured and described to detect differences in decomposition and microbial activity. Morphology of the surface horizons was distinctly different, and accumulation of litter around rock fragments was not continuous across the surface. The O horizons from each site show dissimilarity in decomposition, but soil organic carbon was generally similar within the mineral soils. Results indicate that surface rock fragments increased soil and

near-surface temperatures, and controlled moisture movement and retention to a lesser extent. These factors may negatively influence microbial activity, which is dependent on temperature and moisture status in the litter layers around rock fragments, and in the underlying mineral soil. Examination of pyrogenic char samples suggests that surface rock fragments can control or impede the contact between aboveground inputs and underlying mineral soils. In addition, contact with soil microbes that may use char as habitat, can be restricted.

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Chapter 1

1.1 Introduction

The soil surface is an important point of contact between the atmosphere, aboveground biosphere, and underlying soil environment. Inputs to the soil environment that come from aboveground, initially come into contact with whatever material lies at the surface. The soil surface can be covered by materials including live vegetation, decomposing plant matter, and rock fragments. Surface cover acts as a mulch and regulates environmental factors such as temperature and precipitation, and the input of organic and inorganic materials (Brady and Weil, 2008). For example, surface covers are a protective barrier in both natural and agricultural systems for conserving water, reducing erosion, and preventing carbon losses (Zuazo and Pleguezuelo, 2008). Surface covers also serve as habitat, and control the diversity of plants and microorganisms (Brady and Weil, 2008). Surface covers are a substrate that determine the physical distribution and ecosystem function of those organisms (Facelli and Pickett, 1991), and can both impede and promote plant growth through (facilitating or preventing) seedling establishment (Maestre et al., 2003). Organic surface covers also serve as sources of nutrient input to soil, which improves soil health (Hartwig and Ammon, 2002). Understanding the influence of surface cover and differences between types of cover is important to understanding soil and ecosystem function.

1.1.1 Surface Organic Litter

Surface plant litter greatly influences, and is characterized by, the surrounding soil environment. For example, it controls the way nutrients and water move through the soil ecosystem. Moreover, it affects plant germination and community structure through its accumulation patterns (determined by the physical environment), which determine the concentration and success of future seedlings (Facelli and Pickett, 1991). Organic horizons at the soil surface are a common type of surface cover primarily formed from decomposing plant matter, which is cycled by animals and microorganisms. Environmental conditions, biological activity, and qualities of the organic matter determine the rates of accumulation and decomposition. Organic horizons often exist over a wide spectrum of decomposition products in any given soil, and they influence soil formation throughout the profile through leaching and mixing as the organic matter decomposes into humus (Buol et al., 2011). Organic horizons and plant litter are described in US soil taxonomy with the O horizon designation (Soil Survey Staff, 2014), which has limited capacity for details. Other classification systems describing detailed humus forms exist, but are not widely used (Green et al., 1993). Describing O horizons and surface covers in more detail is beneficial for illustrating differences imparted by surface topography and input material.

How and where organic matter accumulates has implications for the establishment of plants and function of ecosystems. Microtopography is an example of a surface condition that can influence the accumulation of plant litter. The successful germination of some plants and their subsequent growth as seedlings has been shown to depend

greatly on small differences in surface relief of soils (Harper et al., 1965; Smith and Capelle, 1992). However, the impact of microtopography is selective between species (Harper et al., 1965), which may imply the importance of relatively heterogeneous or homogeneous landscapes in determining ecosystem properties like plant communities, and the consequent deposition plant litter. Thus, microtopography could be closely linked to the formation of organic horizons.

1.1.2 Soil Organic Matter and Biogeochemistry

Soil organic matter (SOM) is an important factor in carbon cycling. However, the methods and models by which soil organic matter is characterized and observed are changing drastically from historical methods (Lehmann and Kleber, 2015). Environmental factors and soil conditions such as temperature, microbial ecology, and sorption mechanics have become fundamental in understanding SOM turnover (Davidson and Janssens, 2006; Lehmann and Kleber, 2015). In the broadest environmental sense, terrestrial environmental variables are crucial to fluxes in the carbon cycle and climate change (Cao and Woodward, 1998). Soil surface cover is a soil property that may have important implications for these environmental factors.

Soil organic matter was traditionally considered a bi-modal property – either a persistent and stable compound or a readily oxidized metabolite. Recent research trends treat these compounds as an ecosystem property as well as a continuous variable that is subject to the influences of its environment (Schmidt et al., 2011). This is important as soil organic carbon (SOC) becomes an integral factor in a wide variety of fields such as climate modeling, soil chemistry, and landscape ecology. The biogeochemistry of the

carbon cycle is complex, and new models for use in environmental, climate, and soil science fields are emerging to describe the process. The new structure of SOM research connects SOC cycling and the interactions with the surrounding environment that govern it (Schmidt et al., 2011).

Soil organic carbon cycling and stabilization are dependent on an array of environmental and pedogenic factors. SOM is widely recognized as a significant terrestrial carbon stock (Lal, 2008; Settele et al., 2014). This is important to consider alongside the dynamics of organic matter accumulation and decomposition. Carbon stocks (bulk carbon per area) vary in forests depending on productivity, forest type and forest age. Moreover, mountain ecosystems in California with a wet-dry seasonal cycle, such as in the Klamath Mountains, exhibit great spatial and temporal variability in organic carbon. Decomposition of organic carbon is typically inhibited by dry summer weather, and encouraged under winter snowpack, despite cold temperatures (Johnson et al., 2009). Altogether, soil climate and soil carbon properties may be tied to the structure and morphology of soil surface cover, which is also shown to vary with plant community and physical properties across landscapes.

1.1.3 Pyrogenic Carbon

Forest fire effects on soil are shown to persist and consequently affect soil development over long periods (Goforth et al., 2005; Briggs et al., 2012). One persistent material is charcoal (also called black carbon or pyrogenic carbon), which is the product of incomplete combustion of biomass. The material can be persistent in the environment for hundreds of years (Forbes et al., 2006) because its aromatic compounds are resistant

to microbial decomposition (Lehmann et al., 2015). Charcoal can also have a short turnover residence time depending on the conditions of its formation (Preston and Schmidt, 2006). It is now considered as a major component of carbon sequestration in terrestrial ecosystems, as it can comprise a major fraction of organic carbon where fires are a common occurrence (Lehmann et al., 2006; Preston and Schmidt, 2006; MacKenzie et al., 2008).

The manner in which char interacts with its environment is important to its role in soils. In a similar manner to SOM, char research struggles with the same difficulty in characterization and chemical testing (Hammes et al., 2007), and exists on a continuum of particle size and chemical properties (Masiello, 2004). Nutrient cycling through forest soils is shown to be somewhat dependent on the burning of the forest floor (Johnson et al., 2014; Michelotti and Miesel, 2015). The porous characteristics of char have been shown to increase soil cation exchange capacity, water holding capacity, surface area, and microbial activity (Warnock et al., 2007; Atkinson et al., 2010; Joseph et al., 2010; Briggs et al., 2012). Furthermore, long-term accumulation of char in soils increases carbon sequestration and soil fertility (Clough and Condron, 2010; Mao et al., 2012). Char has widespread spatial and temporal impact on soils. Therefore, ground surface properties that control the location (accumulation) and rate of organic litter cycling (through fire) will consequently influence the underlying soil chemical changes.

1.1.4 Surface Rock Fragments

Rock fragments are another type of surface ground cover, which, similar to O horizons, can affect ecosystem processes. Mountain slopes are often covered with rock fragments of various size, where they have been deposited through landslides, stream flow, or left as an erosional lag deposit from in situ weathering. Depending on the physical process of formation, the soil and rock material can be mixed or sorted by size. This material often comes in the form of major geomorphic features like talus deposits. Talus is known to form through a combination of processes including erosional lag deposits, frost heave, or mass movement that determine their exact morphology (Kirkby and Statham, 1975).

Rock fragments commonly cover desert surfaces in the form of desert pavement – a single layer matrix of rock fragments that forms a protective surface over soil material (Cooke et al., 1993). It most commonly forms in hot, arid deserts, but pavement is known to form in a variety of other climates and environments. Desert pavement is a physical soil feature of fundamental importance in desert ecosystems. Due to their slow rate of formation and repair they can serve as an indicator of disturbances (Cooke et al., 1993). Entrapment of eolian dust by the pavement forms a vesicular horizon, which reduces water infiltration and increases storage of salts, including nitrate (Graham et al., 2008). Other research correlates various desert pavement patterns with specific plant community structures (Wood et al., 2005). This collective research suggests that soil surface cover and ecosystem processes are closely linked.

In desert mountain regions, as described by Blank et al. (1996), and alpine mountain regions, as described by Litaor (1987), eolian dust can fill in the matrix between surface rock fragments and expand the soil depth as a whole through a deposition-uplift process. Dust entrapment by surface rock fragments is wide-spread in arid regions, and research suggests it obstructs water infiltration (Hirmas et al., 2011), whereas surface rock fragments typically promote infiltration (Poesen and Lavee, 1994). The contribution of foreign soil material (i.e., dust) is crucial to the relationship of surface topography and soil formation. Inputs can completely differentiate the topsoil from the subsoil forming directly from parent material (Reynolds et al., 2006). This type of relationship between land surface charactertistics and pedogenesis has been documented in dry, unforested ecosystems where dust is a significant input, but not in forested ecosystems where organic matter inputs substantially contribute to surface conditions.

In agricultural settings, changes in rock fragment cover pattern by (induced by tillage) affect soil water balance. Deep, rock-fragment-covered soils in valleys show low evaporation, and an overall more stable moisture regime (van Wesemael et al., 2000). In natural environments, surface rock fragments increase infiltration and percolation, and prevent evaporation (Cerda, 2001; Sinoga et al., 2010). In addition, burning-induced soil water repellency, a major effect of forest fires, is mitigated by high surface rock fragment cover (Gordillo-Rivero et al., 2014).

Reduced vegetation around rocky soils results in lower accumulation of surface organic matter and microbial biomass, and can even create isolated, barren soil patches

(Ley et al., 2001). However, barren soil patches can remain biologically active enough to maintain nutrient cycling in the ecosystem (Williams et al., 1997). It is known that litter types and nutrient conditions, and soil development and parent material are controls on microbial activity, and thus control the relative stabilization of labile and recalcitrant soil carbon pools (Melillo et al., 1982; Catoni et al., 2015). In addition, organic matter is a good indicator of microbial biomass in vegetated soils, and soil texture is the predominant factor in bare soils (Ley et al., 2001). If the presence of rock fragments over the soil surface influence plant litter and soil properties, they consequently influence microbial activity.

The soil geomorphic feature examined in this research is a surface rock fragment layer overlying soils on mountain backslopes. Soils with overlying rock fragment cover are documented throughout the Klamath National Forest. About 3% of the soil profile descriptions made to document soil mapping in the western Klamath National Forest show a surface layer of rock fragments ranging from gravels to boulders. The layer is often on the order of 10 to 20 cm thick, but can be up to 185 cm thick, depending on the size of the rock fragments, and is usually only one or two fragments thick.

The rock fragments cover the soil in a distinct layer across a continuous, wide topographical contour. The rock fragment layer creates an irregular surface above the soil. The rock layer feature is similar in morphology to talus, which generally exhibits straight slopes, concave bases, and downslope particle sorting from fine to coarse. However, in this case the surface rock fragments vary greatly in concentration and size from one point on the landscape to another. Thus, high variation in surface

microtopography may occur in a relatively small area. In this regard, microtopography across the landscape might govern soil properties in a similar way that geomorphology can determine characteristics such as soil depth or moisture content.

Research directly relating surface rock fragment cover to specific soil processes in mountains is scarce. It is generally underrepresented in considerations of soil morphology, and has no official horizon designation. Most research involving rock fragments focuses on the role of coarse fragments within the soil matrix, and does not consider surface rock fragment cover. Other research focuses on rock mulches and agricultural productivity. In addition, no research compares surface rock fragment cover with the dynamics of surface soil organic layers. Soil mapping in the Klamath region reveals that topography produces vastly different soil types and plant ecosystems. Lee et al. (2004) documented a toposequence near the area used for this research – the study shows that morphological and chemical differences occur in quick transition across different landscape positions. Given the role surface rock fragments have in determining soil properties, it seems plausible that more focused research could also reveal changes in soil and plant ecosystems as a result of microtopographical variation.

1.1.5 Research Objectives

The objective of the research documented here is to determine how surface rock fragment cover on a forested mountain slope transforms ecological processes near the soil surface (compared to continuous organic litter cover) with regards to: 1) soil climate, 2) surface organic litter accumulation, 3) soil particulate organic carbon, and 4) pyrogenic carbon. The objective is addressed primarily in three ways. First, the morphology and

quantity of organic matter is described through classification and physical measurements. Second, the character of soil organic carbon is determined with chemical analysis and scanning electron microscopy. Third, the influence of surface rock fragments on soil climate is examined through soil temperature and soil moisture data.

Chapter 2

2.1 Materials and Methods

2.1.1 Field Methods

Site Selection and Description

The study area lies within the Klamath Mountains physiographic province on a terrane composed mainly of ophiolite (Ando et al., 1983; Quick 1981). Different locations were considered for site selection in the Klamath National Forest. All landscapes in question had one main characteristic – coarse rock fragments covering a sloped soil surface. False color aerial photos, which showed the proportion of surface rock cover, were used to identify such landscapes. The main area scouted, and eventually chosen for suitable research sites was Blue Jay Ridge, near the Scott River and Callahan, Siskiyou County, CA. The ridge has backslopes with various size ranges of rock fragments from cobbles to boulders. The mapped geology consists of partially or completely serpentinized ultramafic rocks, gabbro, and diorite. Areas with large boulders were excluded from sampling due to the difficulty of excavation.

Mean annual precipitation in the area is roughly 1000 mm (Skinner et al., 2006). Most precipitation occurs during the fall and winter months. Mean annual temperature is 10.2 °C (mean min. 1.9 °C, mean max. 18.4 °C) for 1981-2010 (NOAA, 2015). The area is historically susceptible to wildfires. The last burn of the understory near the research sites was in 1998, and was due to natural causes. Some minor human-caused fires occurred elsewhere on the ridge in 1986 and 1989. The fire record name is Bluejay, with

the ID 335763. Dates were determined by map and date records online from a USGS compilation of data collected from several US agencies (USGS, 2016).

Two separate research sites, about 1 km apart, were chosen to establish a comparison between a soil with surface rock fragment cover and a soil with uniform organic litter cover. Figure 1 contains photos of each site showing the difference in ground cover. Both sites were located on backslopes on the same mountain ridge. X-ray fluorescence (XRF) determined that the soil at both sites formed from weathered mafic rock. XRF data from sample rocks at both study sites indicated similar magnesium (around 53% of XRF-detectable elements) and iron contents (around 7% of XRF-detectable elements). The first area chosen, designated “Site 1”, had a continuous rock fragment cover on the ground surface, including sampling locations. The rock fragments ranged in size from cobbles to boulders, and plant litter settled between the rocks. Coordinates for the main soil pit at Site 1 are 41°14’59.5” N, 122°52'22.6” W at an elevation of 1,756 m. Site 1 has a 33% slope with an aspect of 224º. The second area chosen, designated “Site 2”, had no rock fragment cover, but instead had continuous plant litter cover across the surface. Coordinates for the main soil pit at Site 2 are 41°14’31.9” N, 122°52'30.3” W at an elevation of 1,746 m. Site 2 has a 25% slope with an aspect of 310º. The sampling locations at both sites were about 50 m from Klamath National Forest service road 40N17. The perimeter each study site, including all sampling points, extends from the main soil pit by a radius of approximately 25 m. The appendix contains maps and imagery that show the extent of the study area.

The Klamath National Forest soil survey lists the Tangle and Deadfall families as the predominant soil types in the study area. The sample sites are directly located on land mapped as the Tangle family. Soils at both study sites are classified as Typic Haploxerepts according to US soil taxonomy (Soil Survey Staff, 2014).

The plant inventory at Site 1, including overstory, contains mixed conifers: incense cedar (*Calocedrus decurrens*), Douglas-fir (*Pseudotsuga menziesii*), Jeffrey pine (*Pinus jeffreyi*), sugar pine (*Pinus lambertiana*), and white fir (*Abies concolor*). Other species present include huckleberry oak (*Quercus vacciniifolia*), prince's pine (*Chimaphila umbellata*), pinemat manzanita (*Arctostaphylos nevadensis*), serviceberry (*Amelanchier*), and bear grass (*Xerophyllum tenax*). The dominant group is mixed conifer, huckleberry oak, and bear grass. The inventory at Site 2 contains the same tree species with the addition of western white pine (*Pinus monticola*). The understory species are also the same, except serviceberry is lacking. Tree age was recorded for older growth specimens of two prominent species, white fir and sugar pine. At Site 1, sugar pine was 167 yr, and white fir was 89 yr. At Site 2 sugar pine was 111 yr, and white fir was 104 yr.

Soil and Organic Matter Sampling

Soil profiles were described and sampled according to Natural Resource Conservation Service (USDA-NRCS) guidelines (Schoeneberger et al., 2012). The soil pits were established based on these criteria: 1) immediate area free of disturbance from logging, 2) no unusual micro-topography, 3) free of concentrated fire debris, 4) no unusually large rocks, and 5) sites have similar topographical characteristics. One main

soil pit at each site was excavated to about 80+ cm, where subsoil rock content made further digging impractical given time constraints. Pit descriptions included all organic materials and rock fragments above the mineral soil. Four replicate pits were excavated to about 40+ cm, within the first or second B horizon. Five soil pits were sampled at each site – a total of 10 pits overall. All replicate pits were located within 50 m of the original. Suitability for sampling was the main criteria for plot selection. Consequently, plots were not laid out in a specific grid or pattern. Most of the sampling was done closer to the original soil pit, with at least two plots located further away, but within the 50 m radius. The sites are located on slopes; therefore, horizon thickness was measured perpendicular to the sloping surface. After making morphological descriptions, samples were taken from each horizon and stored in plastic bags.

Separate O horizon plots were sampled apart from the soil pits in order to record detailed descriptions and measurements of organic matter. Five replicate plots were sampled within the perimeter established by the soil pits, and sampled using methods from Harmon et al. (1999). Organic plots were 2500 cm^2 (50 cm X 50 cm), and marked off with flag tape to ensure consistent sampling and measurement. These plots were observed for the purposes of classifying the different O horizon layers and measuring their depths. They were also sampled to determine bulk density and total organic litter mass.

Surface Cover Transects

One surface cover transect was laid out at each site to determine proportion of ground covers. The center point of each transect was located three meters downslope of

the main soil pit. The transects were 40 m long and parallel to the slope contour. The nature and type of surface cover was identified and tallied every 50 cm. Surface cover types tallied include rock, organic litter, woody debris, herbs, shrubs, and trees. This does not include tree canopy, but does include saplings in the understory. Rocks and coarse fragments were classified by their size, and depth of organic litter was recorded.

Tree canopy cover was determined using Google Earth aerial imagery by outlining tree canopies with a radius of at least one meter, and then calculating a percentage based on occupied area. The area included at Site 1 was 2,604 m^2, and the area at Site 2 was 2,562 m^2.

Organic Horizon Descriptions

Organic horizons were described in the field at the designated organic horizon plots using the humus forms system described by Green et al. (1993). The system uses more detailed descriptors than the USDA Oi, Oe, and Oa horizons. This approach helps identify genesis, diversity, and structure of the humus. The master designations in this system separate the typical 'O' into three separate horizons of varying decomposition (L, F, and H), and reserve 'O' for wetland organic horizons. L corresponds to an Oi, F corresponds to Oe, and H corresponds to Oa. Subordinate designations are then used to further describe the nature of the material in the horizon. The Results section includes a more detailed description of each designation used in this study.

Designations were assessed visually in the field. Criteria for classification were color, structure, consistence, and flora/biota. Afterward, in the lab, samples were

physically separated into their constituent parts and more closely scrutinized for classification and weight measurements.

Organic Horizon Densities

Organic horizon density samples were taken adjacent to the organic replicate plots. Since the organic material at Site 1 is settled between rocks on the soil surface, retrieving a simple core with every layer was not possible. Instead, bulk density was measured using a "sand bag" method. All organic matter from a small pocket was sampled. Then, the cavity was lined with plastic and filled with sand back to the volume originally occupied by the organic material. The sand was collected separately to be weighed later. The bulk density of the loose sand was calculated with several averaged replicates in order to convert the weight of sand into volume.

Organic layers at Site 2 were sampled as cores using a plastic cylinder. The organic matter around the cylinder was cut so the material could be removed with the surrounding area undisturbed and uncompacted. The depth of the core and separate horizons could be easily measured within in the remaining cavity. Bulk density of individual O horizons was unattainable because individual O horizons were too thin and brittle to easily extract as a core. Alternatively, the weights proportions of individual horizons were calculated from the bulk density samples by separating the litter decomposition grades and weighing the material after sampling.

In the same plots, total O horizon mass and rock cover mass (above soil) was measured and collected in order to calculate organic and rock proportions.

Soil Climate Sensors

Onset HOBO data loggers and sensors were used to measure soil moisture and soil temperature in the field. The moisture sensors were S-SMx-M005 Smart Sensors, and the temperature sensors were Pro v2 U23 Temperature Loggers.

At Site 1, temperature was recorded directly under the surface rock cover layer, and at 50 cm of soil depth. At Site 2, temperature was recorded directly under the O horizon, and at 50 cm of soil depth. The intent was to show temperature differences between rock cover and O horizon cover. Temperature data were logged at one hour intervals. The temperature sensors functioned properly and collected data constantly from 19 Sept. 2014 to 12 July 2016.

Moisture sensors were deployed to represent a range of horizons, depths, and textural classes. At Site 1, soil moisture sensors were placed at the 8-, 20-, and 43-cm depths, corresponding with the A and Bw horizons. At Site 2, soil moisture sensors were placed at the 13-, 27-, and 37-cm depths, also corresponding with the A and Bw horizons. After the first year, the data logger station at Site 1 was corroded, and the data were corrupted. A new logger was deployed on 18 Sept. 2015 and then collected on 12 July 2016 with all the others. Moisture data were logged at an interval of two hours. Full comparative soil moisture data were collected for the 18 Sept. 2015 to 12 July 2016 period.

2.1.2 Laboratory Methods

Bulk Density

Samples for soil bulk density could only be obtained for the top four horizons. Lower horizons were brittle and had a high volume of coarse fragments. The soil clods were collected intact and transported with padding to the lab. Bulk density was determined using a 3D scanning method described by Rossi et al. (2008). In the laboratory, the clods were air-dried and prepared for scanning. Volume was measured with a three-dimensional laser scanning method using a NextEngine Desktop 3D Scanner Model 2020i with Scan StudioHD imaging software. Afterward, the clod was crushed and sieved to weigh the coarse fragments, and the fine material was oven-dried and weighed. Mineral particle density was assumed to be 3.0 g/cm^3, based on measurements made on serpentinized peridotite at nearby locations in the Klamath Mountains by Alexander et al. (1989). Bulk density was calculated with the following equation (Rossi et al., 2008):

$$\rho_b = \frac{W_c - W_g}{V_c - (W_g/3.0)}$$

where:

ρ_b = soil bulk density, $g \cdot cm^{-3}$

W_c = mass of the clod, g

W_g = mass of the coarse fragments, g

V_c = volume of the clod, cm^3

3.0 $g \cdot cm^{-3}$ = assumed average particle density of the coarse fragments

Particle Size Distribution

Particle size distribution of all samples was measured on a Beckman-Coulter LS 13 320 particle size analyzer. Samples were prepared according to a procedure laid out by Gray et al. (2010). Air-dried soil samples were mixed to ensure uniformity, and weighed out to 0.3-0.5 g. The analyzer uses laser diffraction to measure the proportions of different particle sizes by volume, so exact sample sizes are not necessary. Nevertheless, sample weights were recorded to maintain a consistent quantity. Samples were treated with 20 mL of 30% hydrogen peroxide at room temperature for 24 hours, then heated to 70 ºC in a water bath until reduced to 5 mL liquid volume. They were then diluted with DI water to 60 mL, and reduced again to 5 mL. Each sample was then transferred to a small glass vial with DI water and 0.1 g of sodium hexametaphosphate. Samples were then shaken for 24 hours to completely disperse soil aggregates.

On the analyzer, three trials were run and averaged for each sample. Preliminary test runs were performed to determine the best pump speed that could detect the full range of sand sizes without producing much error or variance in other size ranges. A 65% speed was used throughout the tests.

Soil Color

Color was measured for all samples – both organic and mineral – using a Konica Minolta CR-200 Chroma Meter. After being air-dried and sieved to <2 mm, colors of the fine-earth fraction were recorded using the Munsell color system. Digital colorimeters are accurate and consistent with traditional methods of soil color using color charts (Rabenhorst et al., 2015). Organic samples were only measured if they consisted of decomposed material. Decomposed material was ground in a mortar to achieve a uniform consistency and color.

Soil pH

Soil pH was measured with a Mettler Toledo MP220 pH meter and electrode by using the 1:1 soil-to-water method described by Thomas (1996). Air-dried, sieved soil was mixed with equal parts by weight of water. It rested for 10 minutes, and was then measured with the probe by insertion all the way into the solution.

Carbon and Nitrogen

Carbon and nitrogen concentrations in mineral soil samples and O horizon samples were measured on a Thermo-Finnegan Flash EA1112 combustion analyzer. Samples were ground in a mortar, sieved to <2 mm and dried in an oven overnight at 105 °C. Afterward, the samples were weighed out to around 65 mg in small aluminum tins,

stored in a desiccator, and then processed in the analyzer a few days later. Aspartic acid was used as a reference standard. The carbon and nitrogen data are expressed on a mass basis ($g \cdot g^{-1}$). They were used to calculate carbon-nitrogen ratios and bulk carbon storage. Carbon storage per square meter of land area was calculated by summing the total carbon mass in each horizon to a depth of 75 cm by the following equation (modified from Ellert et al., 2001):

$$C = [(\rho_b \cdot conc)/1000] \times V \times F$$

where:

C = carbon mass in horizon, $kg \cdot m^{-2}$

ρ_b = soil bulk density, $g \cdot cm^{-3}$

conc = carbon concentration by weight, $g \cdot g^{-1}$

V = volume of horizon, cm^3

F = fraction of fine soil material volume (to exclude coarse fragments)

Carbon storage was only calculated for the main soil pits, where bulk density samples were retrieved.

Permanganate-oxidizable carbon (POXC) was measured with a procedure described by Culman et al. (2012). The procedure uses potassium permanganate ($KMnO_4$) to fractionate the "active", chemically labile carbon in soil. A solution of 0.2M $KMnO_4$ was made by dissolving $KMnO_4$ into a $CaCl_2$ solution, and pH adjusting with 0.1*N* NaOH. Soil samples of about 2.50 g were mixed with 2.0 mL of the stock solution

and 18.0 mL of water in polypropylene centrifuge tubes. After being shaken for 2 minutes and settled, 0.5 mL of supernatant was diluted to 50 mL. Samples were read on a Thermo Spectronic Genesys 20 spectrophotometer at 550 nm wavelength. Finally, concentrations were calculated based on a standard curve created with dilutions of the stock solution. Calculations of POXC are based on the amount of $KMnO_4$ consumed in the reaction. The concentration of POXC was calculated using the following equation (Culman et al., 2012):

$$POXC = \{0.02 - [a + (b \times Abs)]\} \times 9000 \times (0.02/Wt)$$

where:

POXC = permanganate-oxidizable carbon, $mg \cdot kg^{-1}$ soil

0.02 = initial solution concentration, $mol \cdot L^{-1}$

a = intercept of the standard curve

b = slope of the standard curve

Abs = absorbance of unknowns

9000 = mass of carbon oxidized by 1 mole of MnO^4, mg

0.02 = volume of stock solution reacted, L

Wt = weight of air-dried soil sample, kg

A standard curve was produced with concentrations of 0.005, 0.01, 0.015, 0.02*M* of the same stock reagent used for testing.

Scanning Electron Microscopy

Scanning electron micrographs were collected for pieces of wood char on a Nova NanoSEM 450 scanning electron microscope (SEM). Char samples were retrieved at both sites near the main soil pit from concordant positions in each soil profile. Sampling points for char were: 1) within the mineral soil, 2) on the surface, exposed to the air, and 3) an additional sample resting on mineral soil, but underneath surface rock fragments at Site 1.

Samples were less than 1 mm in size. They were prepared by mounting with colloidal graphite for conduction, and sputter coating with platinum and palladium to allow detection by the instrument. Samples were carefully split in half to show the natural outside surface and the "fresh" inside surface. Both surfaces were observed under the SEM, which revealed the presence of soil particles and microorganisms. Soil microorganisms were identified using descriptions from Silva et al. (2005). Multiple images were taken (at various magnifications) of each sample to show both large and small scale details, and features of interest. Energy-dispersive X-ray spectroscopy (EDS) was used during the imaging on select samples to illustrate the difference in elemental composition of inside and outside surfaces.

2.1.3 Statistical Analysis

The primary statistical tool used to analyze the data was the Mann-Whitney U-test. This test is used with non-parametric datasets, which do not have normal distributions, to test against the null hypothesis between two independent groups. It functions better with small sample sizes, when each group is less than 20. Cases with

presence and absence of rocks over the soil surface were compared. The goal was to determine whether or not observed physical divergences in the morphology of the soils are also reflected by the character of soil organic carbon. Specifically, the values of permanganate-oxidizable carbon and total carbon concentration of mineral soil samples were tested in a variety of statistical combinations.

First, the U-test was performed with every soil sample pooled together, which is 30 samples total (16 at Site 1, 14 at Site 2). Both the POXC and total C concentrations were tested and compared between sites. Second, the samples were grouped by depth/horizon to look for significant differences within a specific portion of soil. The U-test was performed twice – once for surface (A) horizons at 0 cm, and once for deeper (B) horizons at 25 cm. These represented carbon properties from two distinct soil zones. These tests all showed consistent results, and in order to confirm this the POXC fractional values (POXC/total C) were also tested to include a combination of the carbon measurements.

2.2 Results

2.2.1 Soil Morphology

The most striking difference in soil morphology between the two research sites is the horizon material and shape near the soil surface (Table 1). Figure 2 contains photos of the main soil profiles, which show the difference in surface horizonation at each site. Soil profiles at Site 1 all exhibit a distinct surface rock fragment layer above the mineral soil. This rock layer tends to be mixed with O horizon material. In some cases, a portion

of the rock fragment cover extends above all other soil materials, and is labeled in the profile description as “RF” (rock fragments), followed by a very abrupt broken boundary. Otherwise, at the ground surface, plant litter accumulates among catchments between rock fragments. Thus, RF and O horizon materials are distributed throughout the same depths. Below this horizon there is always an abrupt boundary, and the mineral soil horizons start. The boundaries of the mineral horizons at Site 1 tend to be wavy. At Site 2, rock fragments were never present above the surface or in the O horizons. The site was selected for this characteristic. The profiles all start with an O horizon, underlain by mineral horizons. The boundaries of the mineral horizons at Site 2 tend to be smooth.

Generally, Site 1 has a greater range of all color measurements – hue, value, and chroma (Table 1). Colors of the mineral soil at both sites range in hue from 4.2Y to 7.4Y (higher number is more yellow). The average hue of the surface mineral horizon at Site 1 is 6.0Y, and the average at Site 2 is 5.7Y. Average value and chroma of the surface horizons from both sites are very similar. At Site 1 the hue decreases with depth from 6.7Y to 5.6Y with some fluctuation throughout, indicating slightly more redness in the lower horizons. Site 2 does not show a trend with depth, and has small range from 5.6Y in the surface to 6.1Y at depth.

2.2.2 Soil Physical Properties

Particle Size Distribution

Textures of the soils include coarse sandy loam, sandy loam, fine sandy loam, loam, and silt loam (Table 1). The soils do not show a strong trend in particle size with depth. When comparing all near-surface replicate samples, Site 1 shows particle sizes

somewhat evenly distributed between silts and total sand. But, very coarse and coarse sands constitute a higher proportion of sands at Site 1 than at Site 2. Site 2 shows particle size distribution dominated by more silt, and very coarse and coarse sands are a lower proportion than at Site 1. Ranges for the other particle size fractions are much closer in average magnitude across all samples. Clay films were present in the lower B horizons of three of five soil pits at both sites.

Coarse fragments in the soil mineral horizons are similar between the two research sites (Table 2). Average volume of coarse fragments is 58% at Site 1, and 45% at Site 2. Mineral horizons tend to have more gravel than other fragment size. Cobbles and stones in the soil profile are only prominent in some of the soil pits, most of which are at Site 1.

Bulk Density

Bulk densities of all samples range from 0.79 to 1.44 g/cm^3 (Table 2). Site 1 has a weighted (with depth) average density through the top four mineral horizons of 1.24 g/cm^3, and Site 2 has a weighted average of 1.30 g/cm^3 through the top four mineral horizons. Site 1 has greater bulk density in the upper most A horizon (1.20 $g \cdot cm^{-3}$) compared to Site 2 (0.79 $g \cdot cm^{-3}$). Bulk densities at Site 1 do not follow a linear trend with depth, whereas Site 2 bulk densities increase down the profile into the Bw horizons. The difference in mineral soil bulk density between the sites is greatest in the upper portion of the soil profiles (first two horizons). The A horizons from each site differ by 0.40 g/cm^3. The deepest bulk density samples (B horizons) from each site differ by only 0.19 g/cm^3.

Soil Temperatures

Temperature data show clear differences between sites, both in magnitude and frequency of changes (Table 3; Figure 3). Mean annual temperature is greater for Site 1 than Site 2 by 4.4ºC at the soil surface and 3.3ºC at 50-cm soil depth. At Site 1, mean annual temperature at the soil surface is greater than at the 50-cm depth by 0.8ºC. At Site 2, mean annual temperature at the soil surface is greater than at the 50-cm depth by 0.3ºC. Seasonal averages show more variation in terms of the highest and lowest averages. The greatest range of temperatures occurred at the soil surface of Site 1. Conversely, Site 2 soil temperature changes were more subdued. This can be visualized by separating the temperatures by seasonal designations: December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON). Temperature ranges are most pronounced during the summer months. For example, Site 1 soil surface temperatures in JJA ranged from 41.9ºC to 8.1ºC. Site 2 surface temperatures in JJA had a narrower range with a high of 19.1ºC and a low of 7.0ºC. The relationships of temperature between sites is rather consistent during all seasons/months. Overall, soil surface temperatures were more variable than soil temperatures at the 50-cm depth.

Another important distinction in the relation of temperature between sites is the day-to-day fluctuation of temperatures at the soil surface. By comparing both sites' data on a short temporal scale (on the order of days), one can see higher magnitudes of diurnal fluctuations of temperature at Site 1 (Figure 4). In addition, there are times at Site 2 when the diurnal fluctuations are almost entirely subdued. In other words, within a given

time span, soil surface temperatures at Site 2 hold more constant, while those at Site 1 are more susceptible to diurnal fluctuations. The months of SON and DJF generally showed a lower difference in magnitude between study sites. The months of MAM and JJA showed very pronounced difference in magnitude. Deeper within the soil (50 cm), temperatures were not prone to this difference because diurnal fluctuation of those temperatures was well under 1.0ºC (Figure 5).

The sensors were active for almost 2 full years. The main inconsistency between the two years was during the winter months. During the early months of 2015, temperature fluctuated daily. However, during the early months of 2016, the frequent daily fluctuation did not occur. Instead, temperature remained at a mostly constant level from early December to early April.

Soil Moisture

Soil moisture data show that both research sites have similar average moisture contents across all three depths and duration of recording (Table 4; Figure 6). Site 1 averaged 0.16 m^3/m^3, and Site 2 averaged 0.18 m^3/m^3 when calculated for all three top horizons. Site 2 held relatively more moisture at the lowest depths measured (43cm and 37cm), and Site 1 held moisture content a little more evenly throughout the profile (Table 4). The horizon consistently holding the least water at Site 1 was the deepest measured depth (43cm). The horizon consistently holding the least water at Site 2 was the shallowest measured depth (13cm). Site 1 had a wider range of moisture content from 0.03 to 0.46 m^3/m^3. Site 2 had a narrower range from 0.03 to 0.31 m^3/m^3.

Short time-scale comparisons indicate some difference in fluctuations of water content between research sites (Figure 7). In the A horizons, regardless of the time of year, Site 1 is more prone to daily fluctuation of moisture and precipitation events. Site 2 does not often show short-term fluctuations, and magnitude of change is less. Site 2 can also lag behind in response to changes in moisture – this can be seen in December and May.

2.2.3 Surface Organic Properties

Surface Cover

There is no bare ground anywhere on either transect. At Site 1, rock fragments make up the largest fraction of surface cover with 40%. Shrubs are the second largest fraction with 25% and plant litter is the third with 24%. About half of the litter covers soil, and half covers rock fragments. The remaining surface cover consists of woody material and bear grass. At Site 2, rock fragments only make up 4% of the surface cover. Litter covers the largest fraction of surface cover with 43%. Most of it covers soil rather than rock fragments. Shrubs are the second largest fraction with 33%. The remainder consists of woody material, herbs, bear grass, pines cones, and small trees. Tree canopy cover at Site 1 was 30%, and canopy cover at Site 2 was 69%.

Classification and Diversity

Organic horizons showed multiple grades of organic material. Table 5 shows the assortment of horizons identified in the organic sample plots. The descriptions are taken from Green et al. (1993). Site 2 shows a wider range of organic materials in terms of the degree of decomposition. Site 2 has a total of 6 types of organic horizons across a total

of 14 total horizons samples, and Site 1 has 5 types of organic horizons across 10 total horizon samples (Table 6).

Despite having equal numbers of replicate plots at each site, the greater total horizons alone indicates more diversity in development of organic matter at Site 2. Site 2 contained the most decomposed material and a higher proportion of moderately decomposed horizons. Perhaps the most important observation is the presence of matted structure in 5 of the horizons, which is caused by a prominent presence of mycelial fungi in 5 of the 13 horizons. This contrasts with Site 1, which had no apparent fungal structures. Instead, Site 1 has more zoogenous, woody, and freshly accreted material.

Weights and Densities

Organic plots at Site 2, on average, had over twice as much organic mass (per 2500 cm^2) above the soil surface as at Site 1 (Table 7). However, the range of total mass values is much greater at Site 2. Site 1 had an O horizon bulk density range of 0.05–0.12 g/cm^3 and a mean value of 0.08 g/cm^3. Site 2 had a range of 0.09–0.13 g/cm^3 and a mean value of 0.10 g/cm^3 (Table 1.5). Mean values only differ by 0.02 g/cm^3. The largest difference in density of any two samples is 0.08 g/cm^3. These values appear small in magnitude and insignificant when compared to measurements on mineral samples, and mineral samples differ by a much larger magnitude. However, if one considers the differences in magnitude of organic and mineral bulk densities, those small differences may actually be substantial. In other words, the range in organic bulk densities is large in the context of the small magnitude of values – it constitutes a large proportion. The range of values is larger than the base value of some samples.

The relative weight contribution (to total litter mass) of individual types of O horizons differs considerably between sites (Table 7). Site 1 shows a more skewed distribution than Site 2. The L horizons make up almost 75% of the mass, with F horizons making up the remaining quarter. At Site 2, the distribution between different grades of material is much more even. L and F horizons are each about 37% of the mass, and the H horizons make up last quarter. Clearly, there is a difference in the relative abundance of decomposed material between the two sites. At Site 1, fresh material is the significant majority of mass (~75%), whereas at Site 2 the relationship is reversed, and decomposed material is the majority (~65%).

2.2.4 Soil Chemical Properties

Carbon and Nitrogen

Carbon and nitrogen contents initially decrease with increasing depth at a similar rate in both soils, but Site 2 has more carbon and nitrogen below the 20-cm depth (Figure 8). Total carbon concentration was not found to be significantly different between the study sites (Mann-Whitney U test; $p \leq 0.05$).

Carbon and POXC concentrations are positively associated at both sites (Figure 9). R^2 values for the regressions are 0.84 for Site 1 and 0.81 for Site 2. Site 1 shows a slightly higher ratio of POXC to total carbon content than Site 2. There are two outlier points, which occur at a surface A horizon for each site.

POXC concentration decreases with increasing depth in similar fashion at both sites (Figure 10). POXC at Site 1 barely drops below that of Site 2 around 30 cm depth, and then rises above it at lower depths. Both sites show some slight fluctuation in POXC

concentration below the A horizons. There is no steady increase or decrease. Plots of POXC as a fraction of total carbon concentration in soil reveal mirrored fluctuations between sites (Figure 11); i.e., maxima in the ratio of POXC to total C at one study site correspond to minima at the other. POXC was not found to be significantly different in any horizons when compared between sites (Mann-Whitney U test; $p \leq 0.05$).

Although carbon and nitrogen values are not significantly different between study sites, carbon-to-nitrogen ratio (C:N) varies with depth for both soils (Figure 12). There are distinctly different trends in C:N change with depth. Site 1 shows an overall increase in C:N with increasing depth, and Site 2 shows an overall (and more steady) decrease with increasing depth. The pattern of C:N in Site 1 mirrors the trend of POXC. Appendix 1 shows raw carbon and nitrogen data.

Carbon storage in the mineral soil differs between sites. Site 1 stores 1.03 kg/m^2, and Site 2 stores more than twice that amount, 2.66 kg/m^2. This is the carbon stored to a depth of 75 cm per square meter of land surface area. This difference was found to be statistically significant with the Mann-Whitney U-test.

Soil pH

The soil pH at Site 1 ranges from 6.05 at the surface to 6.70 at the lowest sampled depth. The pH increases at a steeper rate near the surface than at depth, where the rate of increase begins to level off. At Site 2 it ranges from 5.01 at the surface to 6.05 at the lowest sampled depth. There is a fluctuation in the middle depths, followed by a sharp increase in the lowest horizon (Table 2). Average pH value (weighted with horizon thickness) is higher for Site 1 at 6.42 (including replicates). All replicate samples fall

within the range of the main samples. Average pH value (weighted with horizon thickness) for Site 2 is 5.47.

2.2.5 Pyrogenic Carbon

Scanning Electron Microscopy

The SEM imagery of the outer exterior of char particle samples shows components including bacterial and fungal colonies, filamentous bacteria, mycelial fungi, and soil particles (Table 8). Depending on where the sample was located in the soil profile, different materials and organisms may be present or absent. Contrasting the interior and exterior of the particles shows that organisms can penetrate the particle exterior and colonize the inside cavities of the relic lignin structure.

The primary characteristic discovered from microscopy samples is the difference in the diversity of material accumulating on char and how location in the soil profile relates to the material char accumulates. The ground surface sample at Site 1 (#2, Table 8), taken from above organic litter and rock fragment layer, had only trace amounts foreign organic matter accumulated anywhere on it (Figure 13; Figure 14). There are minute quantities of mineral soil particles, and fungal and plant structures. Most of the char is "bare" remnant lignin structure. Conversely, the ground surface sample of Site 2 (#9, #10, Table 8), taken from above the organic litter layer, is covered in a crust of mineral soil particles on the exterior of the char fragment, which also harbors a number of soil microbes (Figure 15; Figure 16). Visible constituents are fungal structures, and chains and colonies of bacterial groupings. Where broken, the char shows a clean interior much like the former Site 1 ground surface sample.

Cross-sectional views of char particles from within the soil profile show that mineral and organic material has deeply penetrated the exterior edge. The material does not form a thick, uniform coating as it does on the outsides, but mineral grains, bacteria, and fungi are clearly visible. As one would expect, the exteriors of these particles are covered with a diverse mixture of material. Mineral grains consistently coat most of the exterior. Amongst the minerals are very abundant bacterial colonies and fungal structures. The sample from Site 1 appears to have a greater proportion of organic material relative to minerals, with complex bacterial crusts and colonies (Figure 17; Figure 18). The Site 2 sample has less complex structures, but mineral crusts, bacteria, and mycelial fungi are present throughout (Figure 19; Figure 20).

The samples taken from directly underneath rock cover at Site 1 show an accumulation different from the samples both at the ground surface and within the soil. Mineral material has not accumulated on the particle, but fungal hyphae are very prominent on the exterior (Figure 21; Figure 22). They do not penetrate the inside of the particle.

Energy-dispersive X-ray (EDX) Spectroscopy

Table 9 provides a list of elements present in each specimen, as revealed by the EDX. The elements that all specimens have in common are: carbon, calcium, oxygen, magnesium, aluminum, and silicon. These are present in the residual organic structure of the char and mineral particles present in various amounts on the char exterior. On the ground surface samples (#2, #9, #10), the "clean" interior of char particles from Site 2

contain manganese, sodium, potassium, and iron. These elements are absent from the Site 1 sample. These elements are likely from some amount of plant or fungal matter that has contaminated the interior area of the particle.

Of the samples taken from within the soil profile the Site 1 specimen contains sulfur and manganese, while the Site 2 specimen contains titanium and sodium. This inconsistency might be from the prevalence of organic matter in the Site 1 sample and, conversely, more mineral matter in the Site 2 sample.

The Site 1 specimen from underneath surface rock cover only has one element more than the ground surface specimen – potassium. Although fungal mycelia cover the exterior of the particle, no other microorganisms or litter material really adhered to the surfaces of the char's structure.

When comparing different parts of the same specimen, relative abundance of some elements changes, but there is generally no difference in the array of elements present. For example, the specimens from within the mineral soil show the same array of elements whether observed with the EDS on the altered exterior of the particle, or on the interior of the particle where it appears to have less debris. Soil and organisms seem able to penetrate the particles in all cases.

2.3 Discussion

2.3.1 Soil Morphology and Physical Soil Properties

The morphologies of the near-surface horizons are most variable and distinct between sites. The upper horizons at Site 1 exhibit much more horizontal irregularity with wavy, irregular, and broken boundaries. The mineral soil is buffered from the air and organic litter by a distinct layer of surface rock fragments. Material from O and A horizons tend to be mixed in some voids among the surface rock fragments. These conditions are related to spatial and temporal variations in temperature and moisture.

Mean, maximum, and range of soil temperatures were always greater at Site 1 than Site 2, both at the soil surface and in corresponding subsoil (Table 3). Minimum temperatures were also always greater in the subsoil at Site 1, but not at the soil surface. Short-term diurnal temperature swings near the surface occurred at both sites, across all seasons. However, during the winter months, probably under snowpack, diurnal fluctuation at Site 2 was a little more subdued than at Site 1. Different surface cover types affect the regulation of diurnal temperature change. Organic litter protects underlying soils from temperature extremes, reducing the diurnal fluctuation (Brady and Weil, 2008). Surface rock fragments have a relatively greater thermal conductivity than fine soil material and organic litter, which have insulating pore (air) space. The thermal conductivity and heat capacity of rock material increases the absorption of shortwave radiation relative to fine soil or litter, thus increasing soil temperatures (Lamb and Chapman, 1943; Balland and Arp, 2005). Considering surface cover alone, the results agree with expected temperature variations. The high proportion of surface rock

fragment cover at Site 1 increases heat transfer to the underlying soil. In addition, longwave radiation is able to escape more quickly, creating a high range of diurnal fluctuation. However, differences in canopy cover are a major consideration, which are discussed later.

Within the A horizons, more moisture was retained at Site 1 where the surface rock fragment cover is present. Site 1 had a greater range of moisture content, and showed faster, more frequent response to moisture changes and precipitation events. Multiple studies have shown that the plants and rock fragments on slopes increase hydrological discontinuity over space (Cerda 2001; Sinoga et al., 2010). Rocky soil exhibits more "flashy" changes in moisture during precipitation events. Van Wesemael et al. (2000) modeled erosion and hydrology on slopes to show that stoniness within the soil increases water infiltration, and stoniness above the soil surface decreases evaporation. Around Lassen Peak in California (an environment similar to the Klamath Mountains), moisture evaporation was shown to decrease under surface rock fragment cover. Surface rock fragments disrupt capillary water movement to the soil surface by increasing air space above the soil (Perez, 1998). Additionally, in dry environments, lateral heat and moisture flow increase condensation below rock fragments (Jury and Bellantuoni, 1976a; Jury and Bellantuoni, 1976b; Nobel et al., 1992). Temperatures below rock fragments can drop rapidly, and this possibly facilitates moisture retention near the surface at Site 1.

Both sites in this study have similar soil texture and coarse fragment contents within the subsoil, which leaves the surface properties as the primary control on water

movement through the soil. The influence of the O horizons on soil moisture is also important to consider. Organic litter can absorb water, diminishing infiltration and plant-available water (Facelli and Pickett, 1991). It is also important to note that porosity of rock can affect absorption of water, and color (albedo) of the rocks can affect the absorption of shortwave radiation (Kemper et al., 1994). This shifts the dynamics of soil moisture and temperature under surface rock fragment layers depending on the geology of an area. The parent material in this study consists of dense, dark-colored rocks, similar to the color of the organic litter. They likely would not influence soil moisture values by absorbing water.

Greater retention of near-surface moisture at Site 1 matches the findings of Perez (1998) that showed decreased evaporation under surface rock fragment cover. Additionally, faster water infiltration and percolation, suggested by the amplified response to precipitation (at Site 1), is consistent with findings of van Wesemael et al. (2000). Furthermore, the short-term variations in soil moisture were more frequent near the surface at Site 1 (this was consistent across seasons). Short-term fluctuation magnitudes in the deeper horizons were very similar between study sites. This is evidence that surface rock fragments have minimal effects on moisture and temperature in the subsoil, at least in the short term.

Canopy cover and solar input is a critical consideration. Canopy cover is much less at Site 1 (30% vs. 69%), which would allow more incoming shortwave radiation to the overall land surface during the day and more outgoing longwave radiation at night. The instruments were near trees at each site, but the instruments at Site 1 had no canopy

directly above. Therefore, it is difficult to discern the exact contribution surface rock fragment cover may have in temperature fluctuations if it is primarily driven by solar input.

All of these observations relate back to the morphology of surface horizons. The spatial irregularity created by surface rock fragment cover certainly affects the movement of water through the profile by retaining more near the soil surface compared to the soil under organic litter. When describing the differences in surface soil temperature between sites, we must still consider the impact of surface rock fragment cover has on vegetation distribution and canopy. The soils with surface rock fragments tend to show lower vegetation density, which can increase shortwave radiation input.

Organic litter on the forest floor creates an interface that insulates the ground from air temperature and shortwave radiation (Facelli and Pickett, 1991). It also intercepts precipitation depending on its type, quantity, and structure. This increases moisture retention above the soil, countering the ability of SOM content to increase water holding capacity (Walsh and Voight, 1977). Larger, denser O horizons at Site 2 accentuate the retention of moisture in the litter. Moreover, the only instance of soil temperatures dropping significantly below 0°C occurs at Site 1, where rock fragments around the O horizon cannot insulate the soil.

2.3.2 Organic Horizons and Organic Accumulation

Organic litter appears to accumulate in distinct ways when comparing study sites. Site 2 organic horizon samples contain material that is highly decomposed, whereas Site 1 samples does not. Moreover, the highly decomposed fraction at Site 2 also constitutes

a significant portion (~25%) of the total mass of organic material. SOM accumulation and decomposition are known to depend on environmental factors such as moisture, temperature, origin of material, plant community, and biological and chemical activity (Couteaux et al., 1995; Cortez, 1998; Quideau, et al., 2001; Quideau et al., 2005). Moreover, ecological succession is shown to decrease the diversity and spatial heterogeneity of organic litters in forest ecosystems (Facelli and Carson, 1991). But, the study sites in this research have very similar plant communities and ecological succession, and they are subject to the same climate and weather events. Sampling of total organic litter shows that Site 1 contains, on average, 50% less total litter mass compared to Site 2. This may be caused by a difference in primary production (Binkley, 1995). Aside from this difference, the main factors affecting organic litter appear to be the soil surface conditions, including temperature, moisture, and morphology (surface topography). Data indicate that the actual moisture and thermal inputs at the surface vary between sites. Litter decomposition is known to be a very complex relationship between climate, litter chemistry, and microbial decomposition (Aerts, 1997). However, climate is generally the dominant factor. With other factors being equal, higher temperature leads to increasing decomposition when the environment is moist, and higher temperature leads to decreasing decomposition when the environment is dry (Butenschoen et al., 2011). Furthermore, variable wetting-drying cycles can reduce microbial populations and hinder fungal activity (Schimel et al., 1999). Moisture was not directly measured in the O horizon, but moisture in the A horizon (higher at Site 1, lower at Site 2) may indicate the retention properties of the O horizon. At Site 1 lower litter mass coupled with higher

infiltration around rock fragments would probably reduce moisture retention in the RF/O horizon. The litter is also exposed to more shortwave radiation and fluctuating temperature extremes. During the dry months, June to November, extreme temperature variation could hinder fungal activity (potentially active at low matric potentials) considerably more at Site 1 than at Site 2. During the wet months, December to May, consistently higher temperatures at Site 1 than Site 2 could increase evaporation from the litter, hindering microbial activity at Site 1 more frequently than at Site 2. These dynamics help explain the lack of highly decomposed organic litter at Site 1.

When the individual organic horizons are grouped and inventoried by type of material, we see some clear qualitative differences in diversity. Site 1 has fewer distinct horizons overall, and most of the O horizon mass consists of slightly decomposed material (74%), compared to moderately decomposed material (26%)(Table 1.6). The moderately decomposed horizons at Site 1 contain fewer large masses of mycelia (Table 1.5). This is a very important distinction from Site 2, where there is a greater variety of material exhibiting a wide spectrum of decomposition states, and many masses of mycelia. Fungi are major contributors to the breakdown of lignin, which is shown to decrease in cooler, drier climates where fungal activity increases (Osono, 2007). Individual horizons containing wood constitute 52% of total O horizon mass at Site 1, and only 15% of total O horizon mass at Site 2. Soil temperature was, on average, cooler at Site 2, suggesting fungi are more actively decomposing lignin during the dry months, June to November. At Site 1, where mycelia are scarce, the horizons are friable with a

large proportion of intact wood litter. The litter diversity of Site 1 suggests limited decomposition – organic material is not highly decomposed.

Patchy distribution of organic litter can be caused by a wide variety of processes such as temporal variation in production or variation in biological activity (Facelli and Pickett, 1991). These processes are not a major factor in mature forests, where litter diversity decreases relative to other ecosystems (Facelli and Carson, 1991). Organic horizons at Site 2 may have greater diversity of material (compared to Site 1) due to decomposition, but they are distributed across the soil surface with the same smooth boundary. The surface morphology of horizons at Site 1 shows distribution of litter across a larger depth with wavy transitions between horizons. Additionally, Site 1 had lower litter bulk density in 4 out of 5 plots. Minimal spatial variation in litter layers at Site 2 suggests that surface rock fragments expand the vertical space occupied by litter and orient litter within the voids of the RF/O horizon. The additional vertical space created by surface rock fragments allows for OM to fall beneath the surface (below the surface rock fragment layer), creating an interface where gravel and organic litter mix together and can be suspended by plant roots. At Site 1 there are no extensive flat surfaces upon which organic matter can accumulate and develop structure. In this sense, surface rock fragment cover appears to create conditions of climate and isolation that impede decomposition.

Differences in litter bulk density also indicate differences in how organic material is layered and accumulated at the surface. The bulk density of these materials is very low compared to mineral soil. They differ by only a few hundredths in magnitude, but some

samples are more than twice the value of others. Additionally, the space directly below the surface rock fragment layer contains very loose, mixed material including gravel, litter, and roots. Rock fragment content in mineral soil is known to decrease soil bulk density (Torri et al., 1994; Cerda, 2001). The same might be true of organic litter at the surface of Site 1, which shows lower bulk densities at Site 1. The organic horizon structure at Site 1 seems less compact and more friable than the matted horizons at Site 2. Additionally, the volume underneath the surface rock fragments is not dense as it contains large voids, and both soil and litter.

2.3.3 Microbial Activity, Soil Organic Carbon, and Environmental Conditions

Statistical analysis did not reveal any differences in carbon or POXC values between the study sites. At both study sites, total carbon and POXC correlate closely (R^2 = 0.84, 0.81). Neither site seems to contain a higher or lower proportion of any particular pool of SOC. Despite these similarities, examining the POXC from another perspective reveals interesting trends in spatial distribution. When the proportional values are matched up by horizon or depth, as they are visualized in Figure 1.8, the equivalent depths do vary in POXC contents. There appears to be more spatial heterogeneity in POXC at Site 1. In other words, POXC as a fraction of the total SOC fluctuates more with depth at Site 1 than at Site 2. This is based on comparison of the two main soil pits because they yield the deepest samples. When all total samples are plotted together with depth, both study sites show a wide distribution of POXC values (Figure 1-6). Site 1 has a higher average POXC value, but in general there is not a statistical difference in distribution (Mann-Whitney U test; $p \leq 0.05$). A similar trend occurs with carbon-

nitrogen ratio. The weighted mean values of C:N in all samples are nearly the same. However, when plotted against depth or horizon, C:N values do not follow the same trend between study sites. Site 1 shows spatial heterogeneity with depth.

POXC represents a pool of labile particulate organic carbon that is smaller, heavier, and more stabilized than other fractions of particulate organic carbon. It is useful for identifying environmental change because it has a positive relationship to microbial activity and biomass (Culman et al., 2012). If a higher concentration of POXC at either site did indeed exist, it could indicate that the soil there is cycling SOC at a higher rate. However, there does not appear to be any relation between POXC and the decomposition of organic litter, which is visually distinct between study sites. Again, the important distinction to make is the difference in spatial distribution. Forest organic horizons and surface rock fragments are known to create hydrological, preferential flow paths (Brakensiek and Rawls, 1994; Cerda, 2001; McClain et al., 2003). This might suggest that the rocky surface at Site 1 distributes SOM and soil and litter nutrients irregularly, rather than uniformly, to specific columns in the soil profile between rock fragments. Additionally, the fact that POXC and C:N mirror one another at Site 1 support the significance of POXC as a factor to describe the distribution of SOC in the soil.

Although POXC does not statistically vary between study sites, the bulk carbon storage within the mineral soil does. The soil profile at Site 1 contains much less SOC. This was also true of bulk organic litter and litter separated into O horizons. Multiple studies report various results in relating organic matter accumulation, vegetation, and

soil. Generally, higher vegetation density corresponds with higher quantities of organic matter in and above soil (Binkley, 1995). However, recent research emphasizes the importance of environmental and soil conditions in determining the accumulation and decomposition of SOM. Vegetation is important in determining the quality of SOM and subsequent suitability for decomposition (Quideau et al., 2001), but in alpine environments soil conditions are a dominant factor in SOC turnover (Catoni et al., 2015). Good indicators of microbial activity and decomposition are the environmental factors at work (temperature, moisture, chemistry, etc.), which impact microbial activity (Melillo et al., 1982). We can draw inferences on the rate of decomposition and nutrient cycling at the surface based on those factors. Distribution of vegetation and rock fragments can determine whether microbial activity correlates more with organic matter or mineral matter. In vegetated areas, microbial activity increases with SOM content, but in rock-covered areas microbial activity increases with silt content (Ley et al., 2001). Forested mountain ecosystems contain nutrient hot spots, where moisture, temperature, and nutrient status fluctuate with weather. They are the result of hydrologic flow paths that mobilize reactants (McClain et al., 2003). Microbial activity can even be a source of hot spots (Woodward et al., 2013). The result is spatially heterogeneous soil ecosystems. Surface rock fragments alter the movement of water and heat relative to forest soils with only organic litter as surface cover. Thus, it may be that the soil surface at Site 1 creates patterns where SOM concentrates between or below surface rock fragments, enhancing microbial activity where moisture can collect, and impeding microbial activity everywhere else.

Vegetation density is a likely cause of the difference in carbon storage between the study sites. If there is no major difference in the decomposition of OM, as indicated by POXC, then OM accumulation might just be a matter of input by vegetation. However, the profiles of O horizons at each study site take on strikingly different appearance and structure even though plant communities are very similar. In addition, the chemical properties of SOC are shown to be vertically discontinuous. A model of organic matter stabilization mechanisms by von Lutzow et al. (2008) shows that the controls on SOC are site- and horizon-specific. In other words, irregularity in the soil profile further accentuates complexity in SOC turnover. Altogether, the observations on moisture, temperature, and surface morphology in this study have implications for the formation of hot spots for the cycling of SOM. Moisture and temperature fluctuation at Site 1 might cause nutrient flow to shift throughout any given season because favorable conditions would become more variable. Extremes like the surface temperature spikes at Site 1 can hinder microbial activity (Melillo et al., 1982). Although the soil is dry during the summer (this also impedes microbial activity), there is still a capacity for condensation and moisture retention below the surface rock fragment layer at Site 1. In this regard, the spatial microtopography created by surface rock fragments potentially facilitates activity below rocks when it would otherwise not occur. It seems plausible that surface rock fragments could positively impact microbial activity in certain places. Temperatures are high and variable directly at the surface, moisture infiltrates through the O horizon and into the A horizon, and biological activity might be physically isolated. Johnson et al. (2011) showed that O horizons alone can create nutrient hot spots where

plant rooting is absent. Rooting from shrubs was more prominent through the O horizons at Site 2, while rooting was more prominent below the surface rock fragment cover at Site 1. Ley et al. (2004) showed that microbial activity can occur unexpectedly during the winter around surface rock fragments. Altogether, this indicates that the soil environment among vegetated surfaces compared to barren surfaces around surface rock fragments could host distinct, seasonal microbial ecosystems, especially in terms of temperature extremes. Nutrients and SOM should be highly susceptible to flow paths and patches formed by surface rock fragment cover. Thus, SOC cycling would occur with more temporal and spatial variability at Site 1 than at Site 2.

The role of pH in decomposition and SOM accumulation at these study sites is not clear. Generally, soil acidity is a result of soil weathering. Weathering lowers pH through release of H and Al ions. Plant litter is not considered a strong indicator of acidity in soil, but can release soluble organic acids in the soil (Ritchie and Dolling, 1985). More importantly, microbial activity is hindered by high soil acidity, and thus is a control on OM decomposition (Robson and Abbott, 1989; Silva et al., 2005). Some nutrients become less available, and specific mineralization processes are negatively affected at soil pH levels of 6.0 and lower (Robson and Abbott, 1989). Burt et al. (2001) measured pH values in other soils in the Klamath region and found a wider range – sometimes a full 2.0 points higher in range than in this study, which includes low depth C horizons that have considerably higher pH. The fine-textured horizons of the Burt et al. (2001) study have pH ranges similar to those of the soils measured herein, around 4.0-6.0. The lower average pH at Site 2 (5.5) compared to Site 1 (6.4), would suggest less

microbial activity and slower SOM turnover (Robson and Abbott, 1989), but Site 2 exhibits more highly decomposed material at the surface, and fungi are acid tolerant (Silva et al., 2005). If both soil pH and temperature favor fungal growth, this agrees with O horizon observations.

2.3.4 Charcoal Characteristics Through the Soil Profile

Scanning electron microscopy revealed differences in the appearance and chemistry of char between the study sites. Depending on where char particles rest in the soil profile, the particles may or may not be altered by organic or soil matter. Specimens from Site 2 consistently have altered particles exhibiting crusts of organic and mineral matter, and microorganisms. The particles taken from above the soil surface at Site 1 (i.e., one from above the surface rock fragments and litter, and another below the rock fragments) have less alteration by organic or mineral matter. First, they exhibited less diversity and abundance of material on the particle surface. Second, they showed fewer elements detected from mineral and organic matter on the surface. Char is composed of carbon, oxygen, hydrogen, and nitrogen, in order of abundance. The ratios of these elements are dependent on the temperature of pyrolysis and source material (Jindo et al., 2014). Other elements present would indicate alteration of the char particle by organic or mineral matter.

Surface rock fragment cover, as shown, can create patchiness in the accumulation and movement of organic material and water around the soil surface. Furthermore, rock fragments impact the severity and distribution of fire effects on underlying and surrounding soils by transferring heat from fire to soil directly below, and also

maintaining post-fire smoldering (Garcia-Moreno et al., 2013; Gordillo-Rivero et al., 2014). Surface rock fragments also accentuate the impacts of low-severity fires compared to high-severity fire on post-fire physical and chemical soil properties (Gordillo-Rivero et al., 2014). Fire can reduce organic matter in the soil surface by up to 65%, increase pH, and alter soil aggregation depending on destruction of SOM and recrystallization of minerals (Granged et al., 2011; Mataix-Solera et al., 2011). If surface rock fragment cover at Site 1 increases the transfer of heat and smoldering of O and A horizons, this would help explain the low organic content and higher pH levels compared to Site 2. The production and accumulation of char at the soil surface is a wildfire effect. Therefore, physical controls on that accumulation and distribution are critical in SOM cycling.

Soils that contain char are known to have higher diversity of biota (Atkinson et al., 2010). Mahmood et al. (2003) showed that microbial activity and bacterial community structure sometimes increase with char, probably as a result of changes in nutrients and pH. Char also serves as an important habitat and substrate for mycelial and mycorrhizal fungi, as these fungi thrive with the surface area and porous structure of char (Warnock et al., 2007). There is little evidence that char directly impacts the proliferation of macrofauna, but macrofauna are important to the physical breakdown and cycling of char (Topoliantz and Ponge, 2005).

Results from SEM imagery and EDX spectra suggest char particles accumulate materials depending on their contact with different substrates. The fact that char above the organic horizons at Site 1 does not support many mycelia is concordant with the

morphology of those organic horizons, which largely lacked mycelia. Conversely, char at Site 2 has abundant mycelia, as do the organic layers there. It is not surprising that the char samples with close soil contact do not vary much between study sites because the char is well incorporated into the soil. Closer contact with the soil increases inhabitation by microorganisms and adherence of mineral particles. This supports the conclusion that substrates (the locations of char in the profile) determine the morphology of char particles and composition of foreign material. Vertical discontinuity created by surface rock fragment cover obstructs the interaction of char with the soil environment in a similar manner that organic litter accumulation is obstructed. If char particles at the surface are less prone to macrofauna activity, and microbial and fungal colonization, they will likely persist in the environment longer. Additionally, if char is unable to accumulate in the mineral soil, physical and chemical changes will be less prominent.

Conclusion

The objective of this study was to discern the effects of surface rock fragment cover on organic matter accumulation, temperature, and moisture in forest soils. Surface rock fragments overlying mountain soils have been studied for their effect on soil temperature and moisture, but not for their role in other soil processes. This study relates temperature and moisture to the accumulation and decomposition of organic litter and SOM, and compares a soil with surface rock fragments as predominant cover to a soil with organic litter as predominant cover. Physical soil properties were documented, and carbon was examined in three forms: organic litter, particulate organic carbon, and pyrogenic carbon. A layer of surface rock fragments overlying forested mountain soils appears to influence the accumulation of SOM primarily through physical controls.

Surface rock fragments increase temperatures of the underlying soil relative to those under organic litter, and allow a high range of temperature fluctuation due to their high heat conductance. Conversely, uniform organic litter over soil contains more air, which insulates the soil from incoming radiation. Soil moisture content under the surface rock fragments is likely affected most by increased infiltration and reduced evaporation. Average moisture is not very different between the study sites, but is distributed differently. The soil surface appears to retain more moisture directly under surface rock fragments in the mineral A horizon. This could also be a result of lower moisture retention by the O horizon because less organic litter collects around rock fragments. A surface rock fragment layer fundamentally changes the manner in which heat and water

interact with the soil surface when compared to a more typical forest floor covered by organic litter.

The relation of surface rock fragments and organic litter is twofold. First, litter around surface rock fragments contains almost no highly-decomposed material. Consistent temperature extremes that occur year-long around rock fragments likely hinder microbial activity. The wetter litter environment of a typical O horizon from December to May could facilitate greater microbial activity, resulting in a higher proportion of highly-decomposed litter and wood debris. In addition, the cooler environment during the hot, dry months could allow for increased fungal activity. Second, a surface rock fragment layer modifies morphology of the soil surface (including mineral soil, rock fragments, and organic litter). The rock fragments determine the physical space that can be occupied by incoming organic matter and plants, creating a soil profile with more discontinuity in the horizons compared to other forest soils. Spatial heterogeneity in the profile may translate to variation in the distribution of inputs downward through the soil.

Organic carbon concentrations were not found to be significantly different between study sites. Microbial activity, as suggested by POXC concentrations, was also not different between study sites. However, spatial distribution of carbon and POXC throughout the soil profiles does not show similarities. The soil with surface rock fragments showed more variation in the fluctuation of C:N ratio and POXC down the profile. The movement of water underneath rock fragments, funneling of organic matter

between surface rock fragments, and the ratios of labile and total carbon suggest that the rocky surface creates more heterogeneous concentration of inputs to the soil.

Pyrogenic carbon observations serve to further illustrate the role of surface rock fragments as an interface between the soil and inputs (both biotic and abiotic). Foreign organic and mineral materials adhering to the exterior and interior surfaces of char suggest that the char may interact differently with the soil depending on its location in the profile.

This research could be expanded in order to more accurately and quantitatively measure the observed differences in soil properties governed by surface rock fragments. First, tree canopy cover was inconsistent between study sites. Greater canopy cover decreases the magnitude of shortwave radiation directly hitting the ground surface, thus partially controlling soil temperatures. Finding additional study sites that eliminate the variable of canopy while maintaining the same variation in surface cover would improve reliability in soil temperature and soil moisture measurements. Second, fire disturbance was also inconsistent. Although char was found at both study sites, the site with surface rock fragment cover contained a greater abundance of burnt material. Quantifying char in the mineral soil and on the surface, across additional sites, could help to show the general influence of surface rock fragments on the generation of pyrogenic carbon. Finally, directly measuring decomposition rates of organic litter would help support inferences made on the biological activity.

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Tables and Figures

Table 1. Selected morphological soil properties for both research sites.

Horizon	Depth	Color, dry	Textural class†	Structure†	Clay films	Roots†	Boundary†
	cm						
Site 1, main soil pit							
RF	40-30	-	-	-	-	-	VAB
RF/O	30-0	5YR 3/1	-	-	-	-	AB
A	0-4	7Y 6/2	l	1fgr	-	3vf	AW
Bw	4-15	7Y 6/3	sil	1fgr	-	2m, 2f, 5vf	AS
Bt1	15-27	6Y 6/3	sil	2fsbk	yes	2m, 1f	AS
Bt2	27-34	5Y 6/4	sil	2fsbk	yes	1f	AW
Bt3	34-50	5Y 6/4	sil	1fsbk	yes	1m, 1f	CS
BC	50-75+	6Y 6/3	sil	1fsbk	yes	2m, 1f	-
Site 1, rep A							
RF/O	12-0	-	-	-	-	-	AW
A	0-12	5Y 6/3	l	1fgr	-	2m, 1f, 5vf	AS
Bw1	12-20	5Y 6/3	cosl	1fsbk	-	6m, 4f, 1vf	AW
Bw2	20-33+	4Y 6/4	l	1fsbk	-	3m, 2f, 2vf	-
Site 1, rep B							
RF	28-18	-	-	-	-	-	VAB
RF/O	18-0	-	-	-	-	-	AB
A	0-22	5Y 6/3	sl	1fgr	-	-	CW
Bw	22-42+	6Y 6/3	cosl	1fsbk	-	-	-
Site 1, rep C							
RF/O	35-0	-	-	-	-	-	AI
A	0-24	6Y 6/3	fsl	1fgr	-	-	AW
Bt1	24-36	6Y 6/3	cosl	1fsbk	yes	-	CS
Bt2	36-56+	5Y 6/3	l	1fsbk	yes	-	-
Site 1, rep D							
RF	30-25	-	-	-	-	-	VAB
RF/O	25-0	-	-	-	-	-	AW
A	0-21	7Y 5/2	l	1fgr	-	-	AW
Bt	21-41+	7Y 6/3	sil	1fsbk	yes	-	-

Site 2, main soil pit							
O	6-0	8YR 3/1	-	-	-	-	AS
A1	0-6	6Y 6/3	sil	1fgr	-	10m, 4f, 7vf	AS
Bw	6-24	6Y 6/3	sil	1fsbk	-	8m, 2f, 6vf	GS
Bt1	24-52	5Y 6/3	l	2msbk	yes	1m, 1f, 4vf	CS
Bt2	52-75	5Y 6/4	sil	2msbk	yes	5m, 1f, 5vf	CS
BC	75-95+	6Y 6/4	sil	1fsbk		3m, 1f, 1vf	-
Site 2, rep A							
O	6-0	-	-	-	-	-	AS
A	0-14	6Y 5/3	sil	1fgr	-	6m, 3f, 4vf	AS
Bw	14-35+	6Y 6/3	sil	1fsbk	-	5m, 2f, 1vf	-
Site 2, rep B							
O	4-0	-	-	-	-	-	VAS
A	0-8	5Y 5/3	l	1fgr	-	-	AS
Bt	8-32+	5Y 6/3	sil	1fsbk	yes	-	-
Site 2, rep C							
O	6-0	-	-	-	-	-	AS
A	0-15	6Y 6/3	l	1fgr	-	-	AW
Bw	15-35+	5Y 6/3	l	1fsbk	-	-	-
Site 2, rep D							
O	8-0	-	-	-	-	-	VAS
A	0-5	6Y 6/3	sil	1fgr	-	-	AW
Bw	5-19	6Y 6/3	sil	1fsbk	-	-	CS
Bt	19-39+	6Y 6/4	sil	2msbk	yes	-	-

†Abbreviations from Schoeneberger et al. (2012).

Table 2. Selected physical and chemical soil properties for both research sites.

Horizon	Depth	Particle size distribution†			Coarse fragments†				Bulk density	pH_w
		Sand	Silt	Clay	GR	CB	ST	Total		
	cm	——%——			——%——				g cm^{-3}	
Site 1, main soil pit										
RF	40-30	-	-	-	0	70	30	100	-	-
RF/O	30-0	-	-	-	15	40	0	55	-	-
A	0-4	47	46	7	60	0	0	60	1.20	6.1
Bw	4-15	21	68	12	65	0	0	65	1.42	6.4
Bt1	15-27	37	54	9	50	15	0	65	1.09	6.6
Bt2	27-34	29	61	11	60	0	0	60	1.25	6.6
Bt3	34-50	34	56	10	60	0	0	60	-	6.7
BC	50-75+	23	67	10	50	10	20	80	-	6.7
Site 1, rep A										
RF/O	12-0	-	-	-	5	75	0	80	-	-
A	0-12	45	47	8	45	0	0	45	-	6.0
Bw1	12-20	55	38	7	20	10	0	30	-	6.1
Bw2	20-33+	47	45	9	15	5	0	20	-	6.3
Site 1, rep B										
RF	28-18	-	-	-	0	90	10	100	-	-
RF/O	18-0	-	-	-	0	60	10	70	-	-
A	0-22	56	38	6	20	0	60	80	-	6.6
Bw	22-42+	60	34	6	30	10	20	60	-	6.4
Site 1, rep C										
RF/O	35-0	-	-	-	0	15	75	90	-	-
A	0-24	53	40	7	40	10	30	80	-	6.1
Bt1	24-36	59	35	6	30	0	10	40	-	6.2
Bt2	36-56+	50	43	8	25	20	0	45	-	6.3
Site 1, rep D										
RF	30-25	-	-	-	5	60	35	100	-	-
RF/O	25-0	-	-	-	5	55	20	80	-	-
A	0-21	51	42	7	30	10	30	70	-	6.5
Bt	21-41+	24	65	12	20	0	40	60	-	6.7

Site 2, main soil pit										
O	6-0	-	-	-	0	0	0	0	-	-
A1	0-6	32	59	9	40	0	0	40	0.79	5.0
Bw	6-24	37	55	8	55	5	0	60	1.25	5.3
Bt1	24-52	44	49	8	20	5	0	25	1.20	5.4
Bt2	52-75	28	64	8	25	0	0	25	1.44	5.2
BC	75-95+	27	67	7	50	30	0	80	-	6.1
Site 2, rep A										
O	6-0	-	-	-	0	0	0	0	-	-
A	0-14	28	62	10	45	0	0	45	-	5.5
Bw	14-35+	35	57	9	35	0	0	35	-	5.6
Site 2, rep B										
O	4-0	-	-	-	0	0	0	0	-	-
A	0-8	46	46	7	20	5	20	45	-	6.1
Bt	8-32+	29	60	11	20	0	20	40	-	5.8
Site 2, rep C										
O	6-0	-	-	-	0	0	0	0	-	-
A	0-15	43	50	7	15	5	50	70	-	4.9
Bw	15-35+	43	49	8	30	0	25	55	-	5.5
Site 2, rep D										
O	8-0	-	-	-	0	0	0	0	-	-
A	0-5	20	69	11	40	10	0	50	-	5.5
Bw	5-19	27	64	10	20	10	0	30	-	5.3
Bt	19-39+	20	68	11	20	5	0	25	-	5.3

†Particle sizes and coarse fragment sizes are based on USDA-NRCS classification.

Table 3. Annual soil temperature means, minimums, and maximums, degrees-C, 2014-2015.

Time series	Site 1						Site 2					
	Surface††			Subsoil‡‡			Surface§§			Subsoil‡‡		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Annual†	11.2	-3.3	41.9	10.4	2.2	19.9	6.8	-0.9	19.1	7.1	2.0	13.6
DJF‡	3.3	-3.3	14.1	4.4	2.2	6.0	2.1	-0.7	5.8	3.3	2.0	4.8
MAM§	8.8	-0.2	24.6	7.4	4.0	13.0	4.5	0.3	13.0	4.4	2.2	8.4
JJL¶	21.5	8.1	41.9	17.2	11.8	19.9	13.2	7.0	19.1	11.8	7.9	13.6
SON#	10.8	-1.4	32.9	12.4	4.5	17.3	7.5	-0.9	17.3	8.9	3.0	12.8

† Annual measurements, 12/14-11/15.

‡ December, January, February.

§ March, April, May.

¶ June, July, August.

September, October, November.

†† Under O horizon and rock fragments.

‡‡ 50 cm depth below mineral soil surface.

§§ Under O horizon.

Table 4. Soil moisture measurements, 9/15-7/16.

Depth (cm)†	mean	min	max
	——————m^3 m^{-3}——————		
Site 1			
7	0.16	0.07	0.45
21	0.17	0.09	0.46
31	0.14	0.03	0.45
Site 2			
3	0.14	0.03	0.20
15	0.20	0.08	0.29
38	0.21	0.09	0.31

† Depth below mineral soil surface.

Table 5. Definitions for organic horizon designations and their consituent materials from Green et al. (1993).

Horizon designations	Property	Definition
Master horizons		
L	-	Upland horizon with relatively fresh plant residues and readily identifiable structure. Equivalent to the Oi horizon.
F	-	Upland horizon with partly decomposed plant residues, and fragmented, but recognizable structure. Equivalent to the Oe horizon
H	-	Upland horizon with well-decomposed plant residues, and generally unrecognizable structure. Equivalent to the Oa horizon.
Subordinate distinctions		
n	New	Newly accreted/deposited, un-fragmented plant material.
v	Variative	Initial decay and discoloration of plant material, and no fragmentation.
m	Mycogenous	Matted structure and firm consistence arising from abundant mycelial fungi and plant roots.
z	Zoogenous	Weak structure and soft consistence created primarily by soil microfauna.
a	Amphi	Intermediate grade between m and z, with moderate structure and consistence with any mixture of plant roots, fungi, and faunal material.
r	Residues	Fine material that still contains some fragmented plant material with dark color and greasy character from humic substances. There is a lower humic content than other H horizons.
w	Wood	Supplementary designation indicating a relatively high proportion of woody debris.

Table 6. Organic horizonation, bulk density, and gross litter weight from 2500 cm^2 plots.

Sample plot	Thickness	Horizon	Gross plot weight	Bulk density†
	cm		g	g cm^{-3}
Site 1, E	0-2	Ln	401.1	0.12
	2-4	Fz		
Site 1, F	0-2	Lnw	1098.4	0.06
	2-7	Fz		
Site 1, G	0-3	Lnw	275.2	0.08
	3-7	Fzw		
Site 1, H	0-3	Ln	385	0.05
	3-6	Lv		
Site 1, I	0-3	Lnw	345.7	0.08
	3-4	Fz		
Site 1 Mean			501.1	0.08
Site 2, E	0-2	Lnw	1051.4	0.10
	2-3	Lv		
	3-5	Fa		
Site 2, F	0-1	Lnw	778.5	0.07
	1-3	Lvw		
	3-4	Fa		
Site 2, G	0-1	Lnw	422.6	0.09
	1-3	Lvw		
Site 2, H	0-1	Lnw	2150.2	0.11
	1-3	Lv		
	3-8	Hr		
Site 2, I	0-2	Lnw	1867.8	0.13
	2-7	Fm		
	7-10	Hr		
Site 2 Mean			1254.1	0.10

† Bulk density was not measured and calculated using the gross weights due to the presence of rocks and wood.

Table 7. Relative weight contribution (to total litter mass) of individual O horizons.

Horizon desgination	Occurrence†	Weight‡	Combined weight	% of total weight
		g	g	
Site 1				
Ln	2	56.2		
Lnw	3	101.5	168.9	73.9
Lv	1	11.2		
Fz	3	43.3	59.8	26.1
Fzw	1	16.5		
Site 2				
Lnw	5	19.5		
Lv	2	47.4	81.9	36.5
Lvw	2	15.1		
Fa	2	38.8	85.1	37.9
Fm	1	46.3		
Hr	2	57.4	57.4	25.6

† Number of times described out of all O horizon samples.

‡ Separated from bulk density samples.

Table 8. Sample identifications, locations, and observations for SEM images, Figures 2.1-2.10.

Sample #	Figure	Site	Location in soil profile	Examined portion of particle	Observations
2	Figure 13	1	Ground surface, above plant litter and rock fragments	Edge between outer surface and inside structure	● No organic or mineral crust
2	Figure 14	1	Ground surface, above plant litter and rock fragments	Outer surface of particle	● No organic or mineral crust ● Trace amounts of organisms and mineral particles
9	Figure 15	2	Ground surface, above plant litter and rock fragments	Boundary between bare outer surface and soil crust	● Mineral crust on outer surface ● Fungal hyphae within crust ● Other surfaces bare
10	Figure 16	2	Ground surface, above plant litter and rock fragments	Inside surface of particle	● Moderately abundant bacteria and fungal hyphae ● Few mineral particles
6	Figure 17	1	Mineral Bt horizon, 27-34 cm	Boundary between inner surface and outer soil crust	● Thick mineral crust on outer surface ● Moderately abundant fungal hyphae on top of crust
5	Figure 18	1	Mineral Bt horizon, 27-34 cm	Inside surface of particle	● Highly abundant bacterial colonies and fungal hypae ● Moderately abundant mineral particles
8	Figure 19	2	Mineral Bt horizon, 24-52 cm	Boundary between inner surface and outer soil crust	● Mineral crust on outer surface ● Bacterial strands on top of crust ● Some bacteria and mineral particles on inner surface
7	Figure 20	2	Mineral Bt horizon, 24-52 cm	Outer surface of particle	● Thin mineral crust on outer surface ● Few bacteria
3	Figure 21	1	Soil surface, above mineral soil, below rock fragments	Outer surface of particle	● Mycelium covering surface ● No mineral particles
4	Figure 22	1	Soil surface, above mineral soil, below rock fragments	Outer and inner surfaces of particle	● Some fungal hyphae on outer surface ● No mineral particles

Table 9. X-ray dispersive spectroscopy of elemental composition on char specimen surfaces denotes presence of the element.

Element	Site 1 Specimens			Site 2 Specimens		
	Site 1 ground surface	Site 1 mineral soil	Site 1 under rock cover	Site 2 ground surface (interior)†	Site 2 ground surface (exterior)‡	Site 2 mineral soil
C	●	●	●	●	●	●
Ca	●	●	●	●	●	●
O	●	●	●	●	●	●
Mg	●	●	●	●	●	●
Al	●	●	●	●	●	●
Si	●	●	●	●	●	●
K		●	●	●	●	●
Mn		●		●	●	
Na				●	●	●
Fe		●		●	●	●
S		●				
Ti					●	●
Ba				●		
Cu					●	

† Target area on exterior of char particle.

‡ Target area on interior of char particle.

● element present

(a)

(b)

Figure 1. Photos showing (a) Site 1 with surface rock fragment cover and (b) Site 2 with organic litter cover.

(a)

(b)

Figure 2. Photos showing (a) wavy and broken horizons at Site 1, and (b) abrupt and smooth horizons at Site 2.

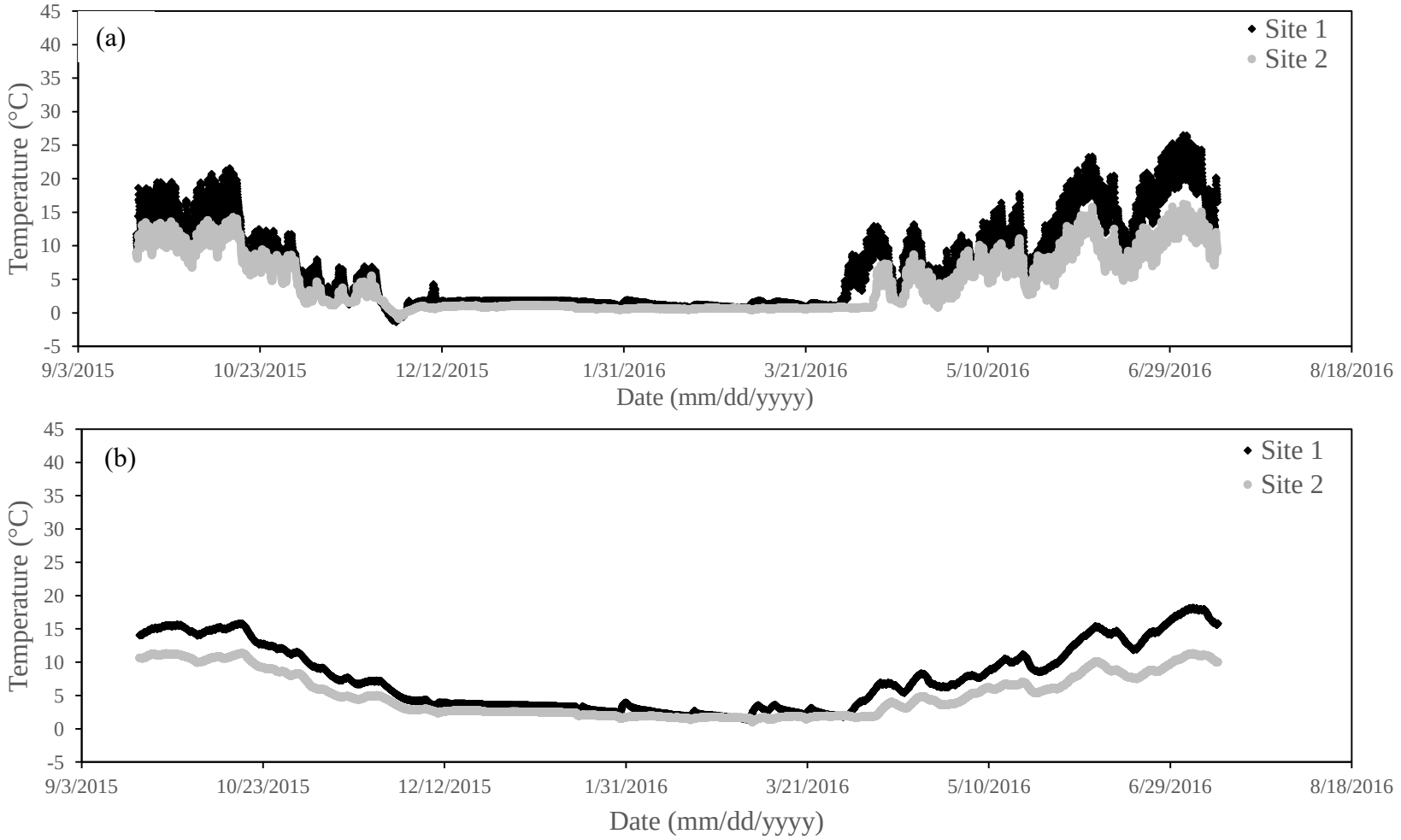


Figure 3. Continuous temperature (a) directly below RF/O horizon, and (b) at 50 cm below mineral soil surface.

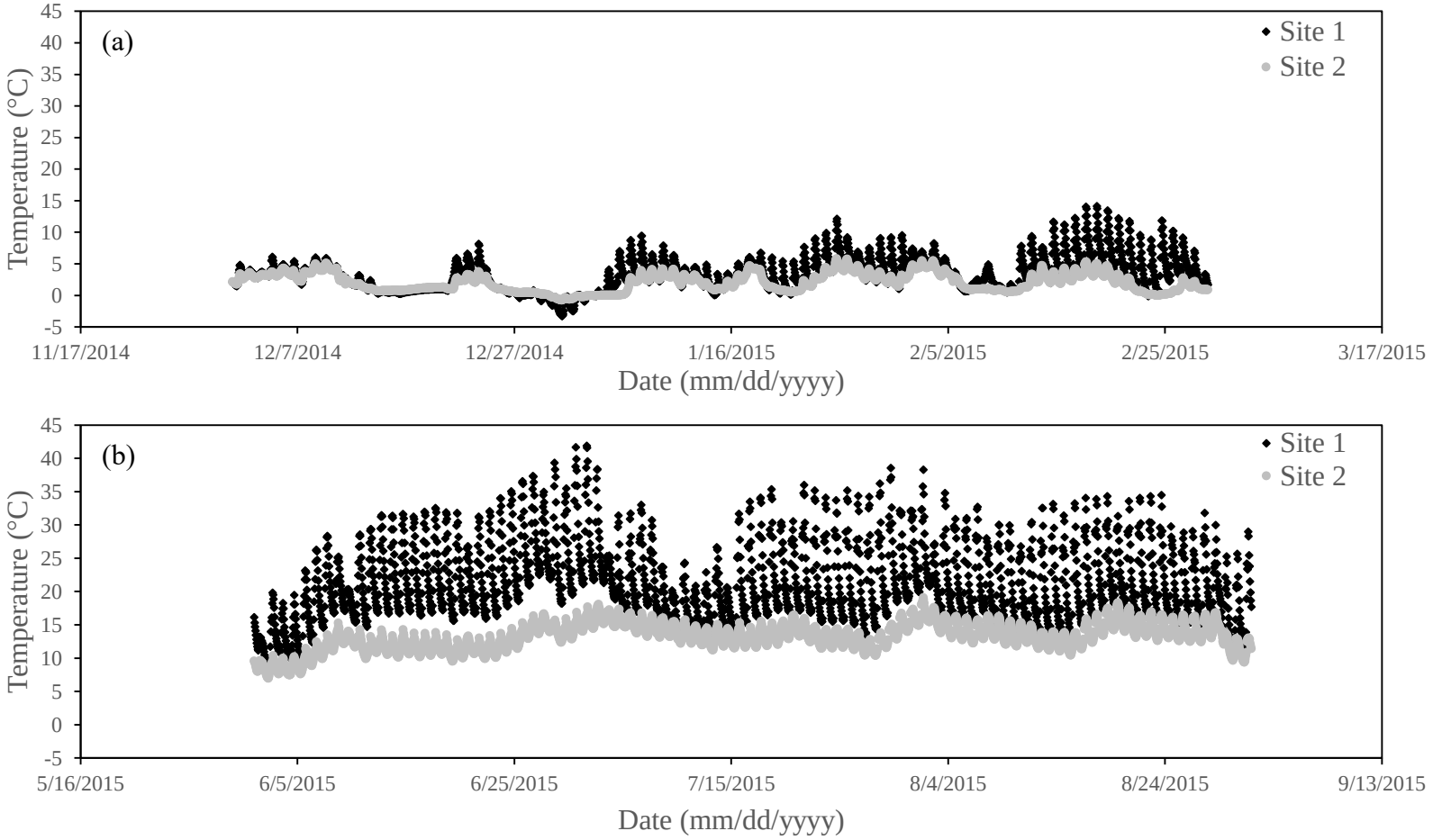


Figure 4. Soil surface (directly below RF/O horizon) temperature for (a) December, January, February, and (b) June, July, August.

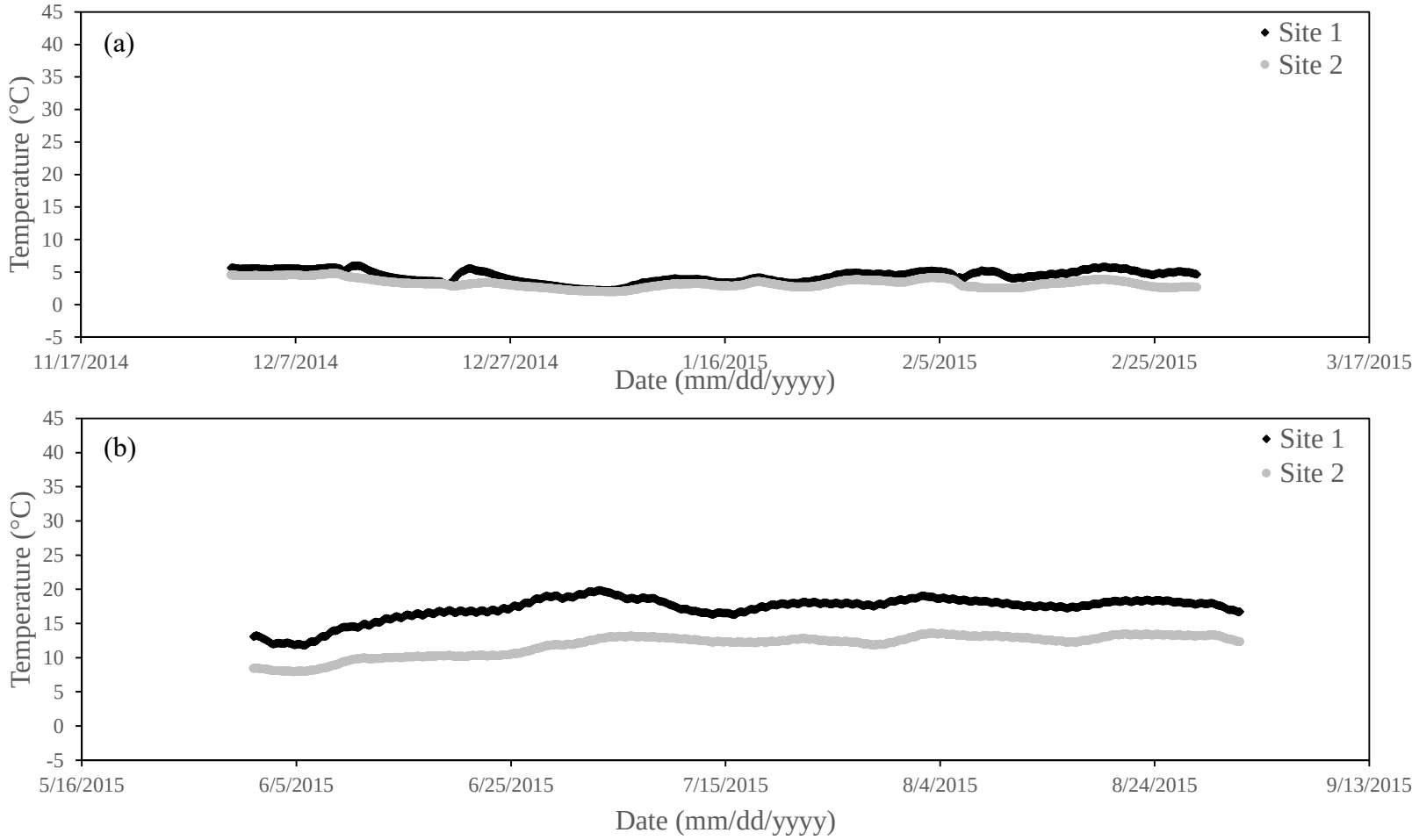


Figure 5. Soil (50 cm below mineral soil surface) temperature for (a) December, January, February, and (b) June, July, August.

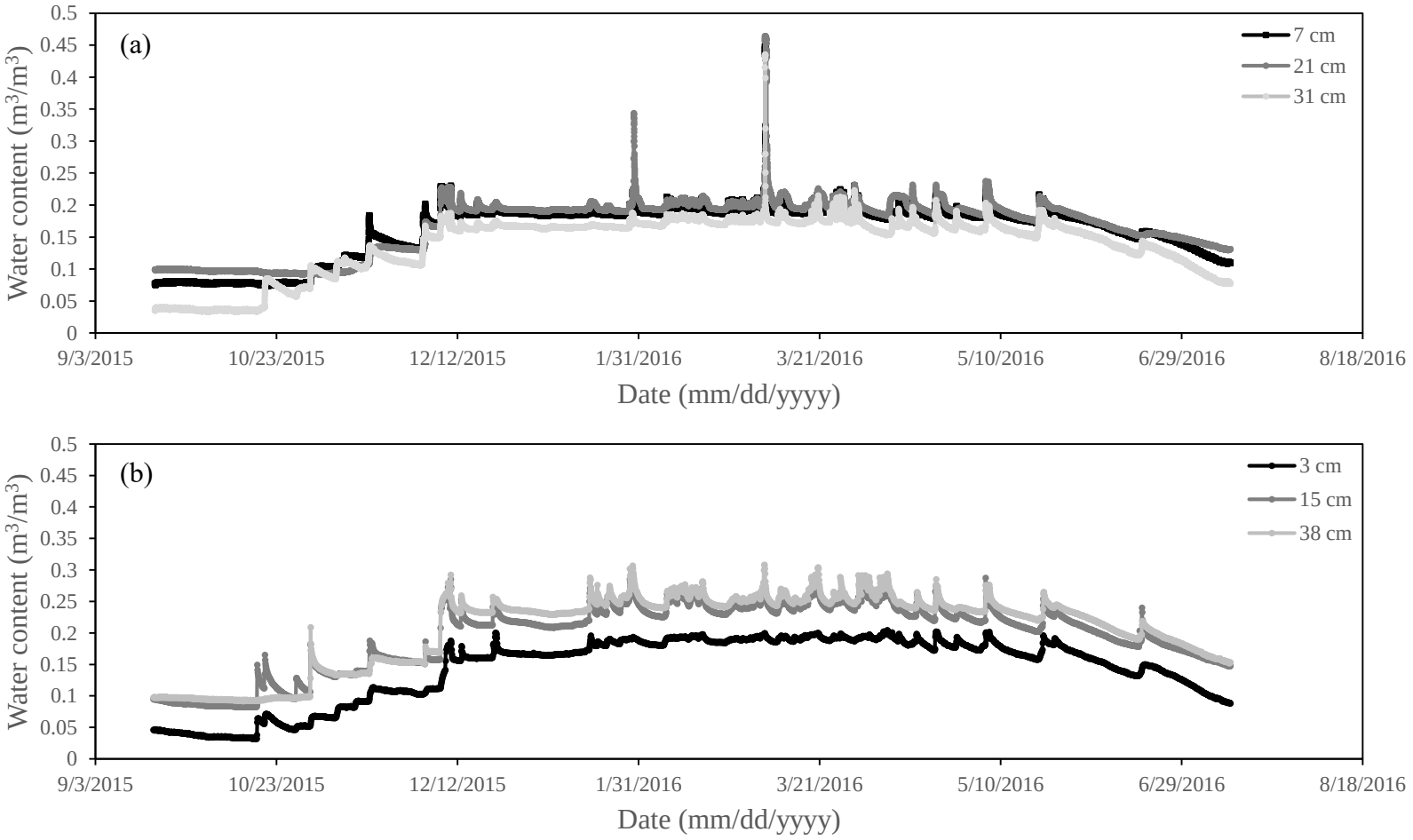


Figure 6. Soil moisture at (a) Site 1 measured at 7 cm, 21 cm, and 31 cm below the soil surface, and at (b) Site 2 measured at 3 cm, 15 cm, and 38 cm below the soil surface.

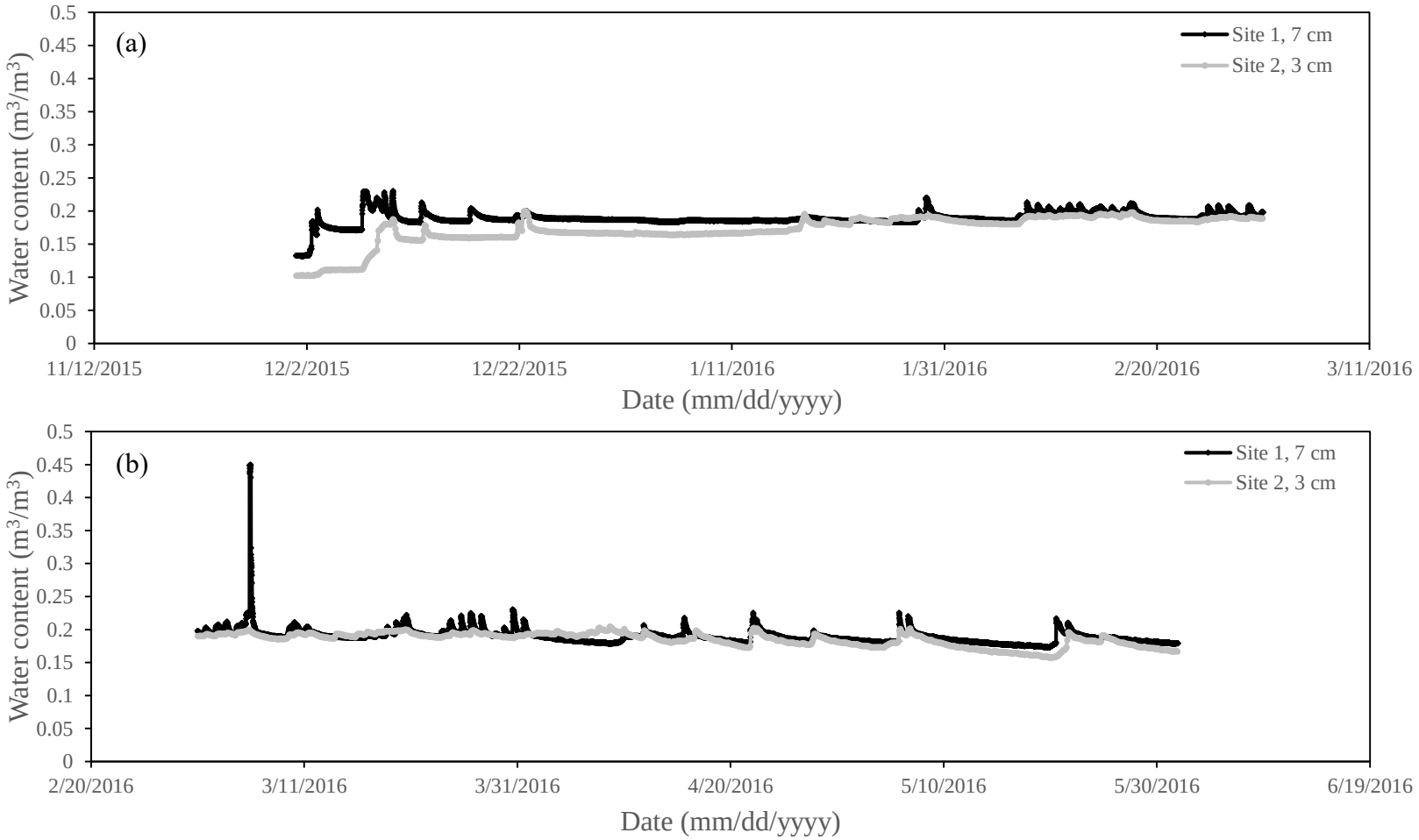


Figure 7. Comparison between study sites of soil moisture in the A horizons for (a) December, January, February, and (b) March, April, May.

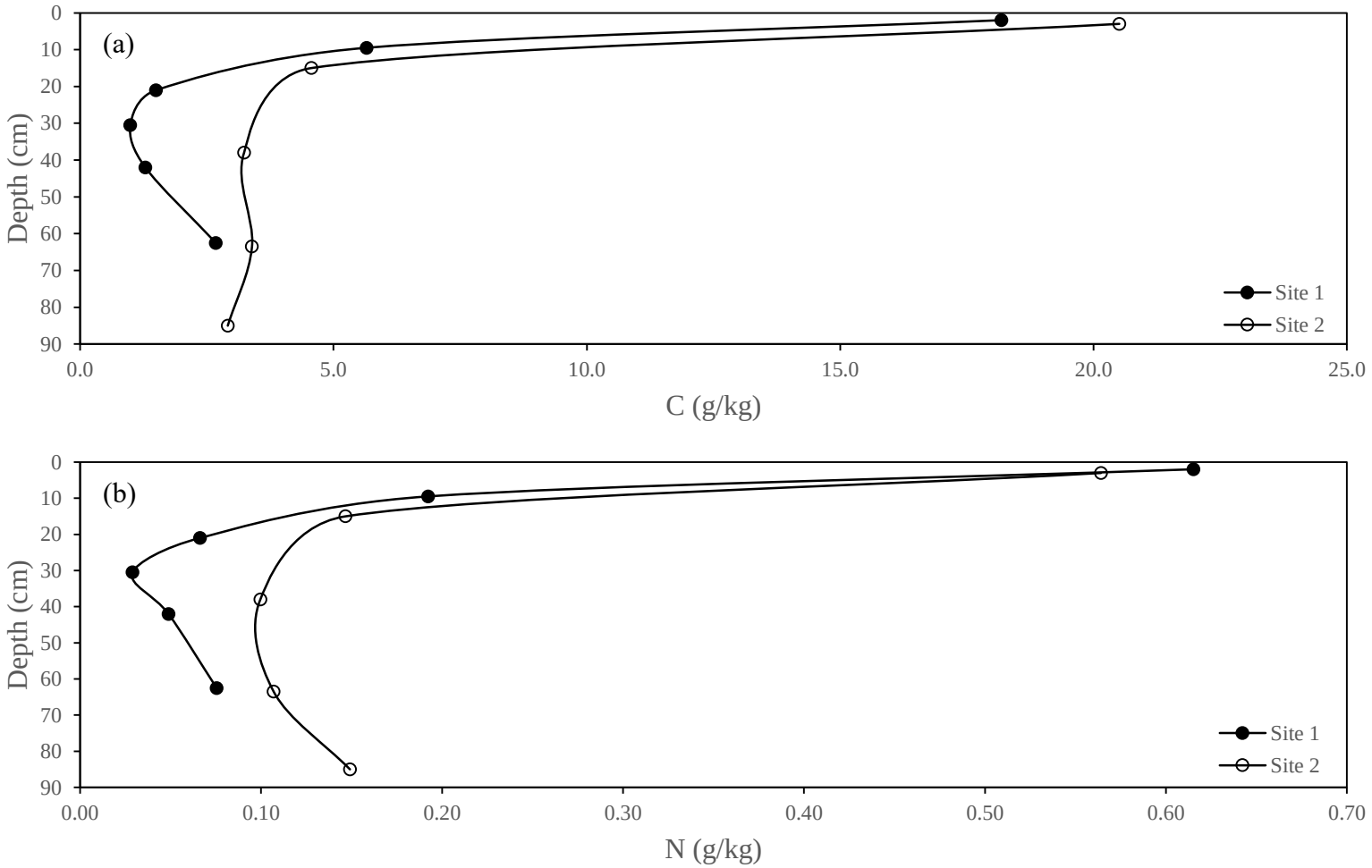


Figure 8. Concentration of (a) carbon and (b) nitrogen in the mineral soil as a function of depth.

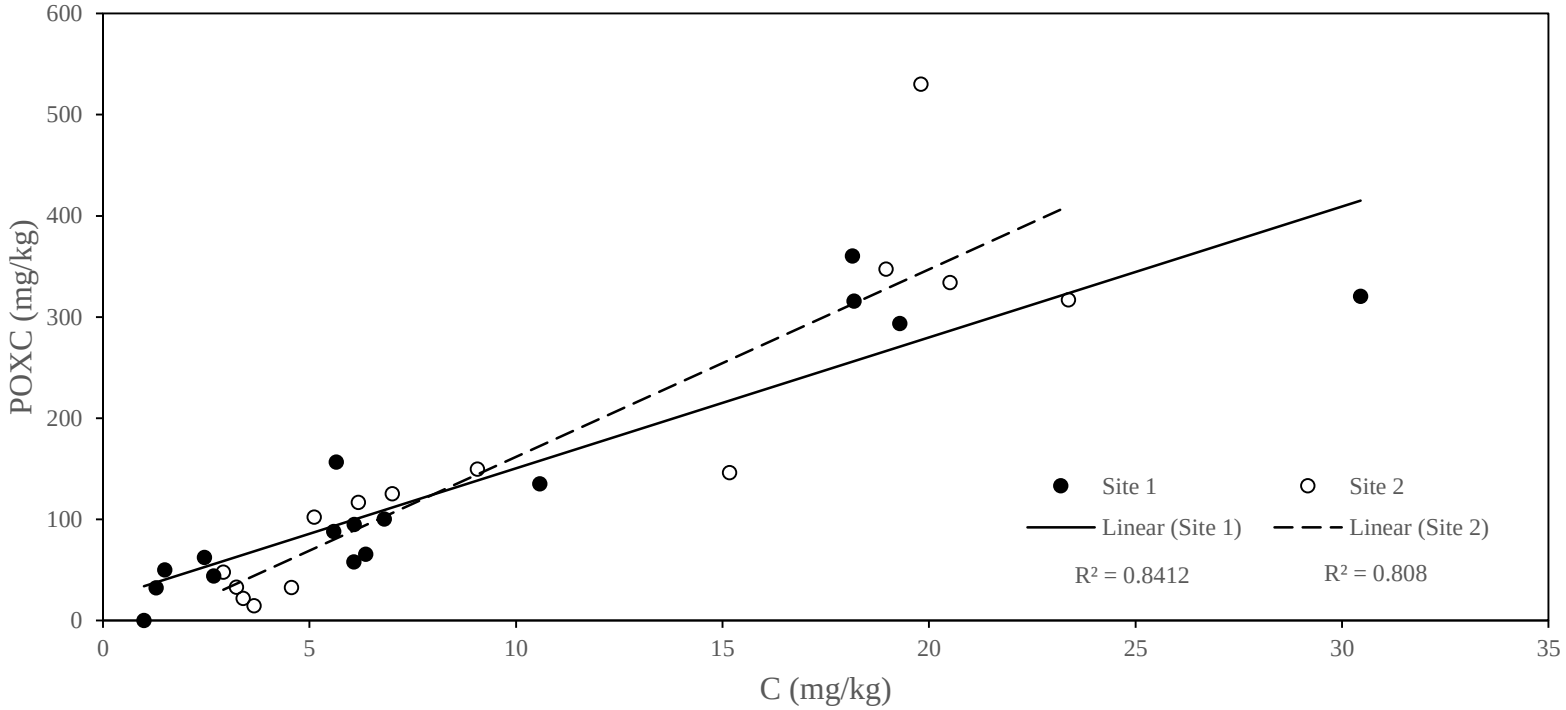


Figure 9. Carbon concentration plotted against POXC concentration for all soil samples.

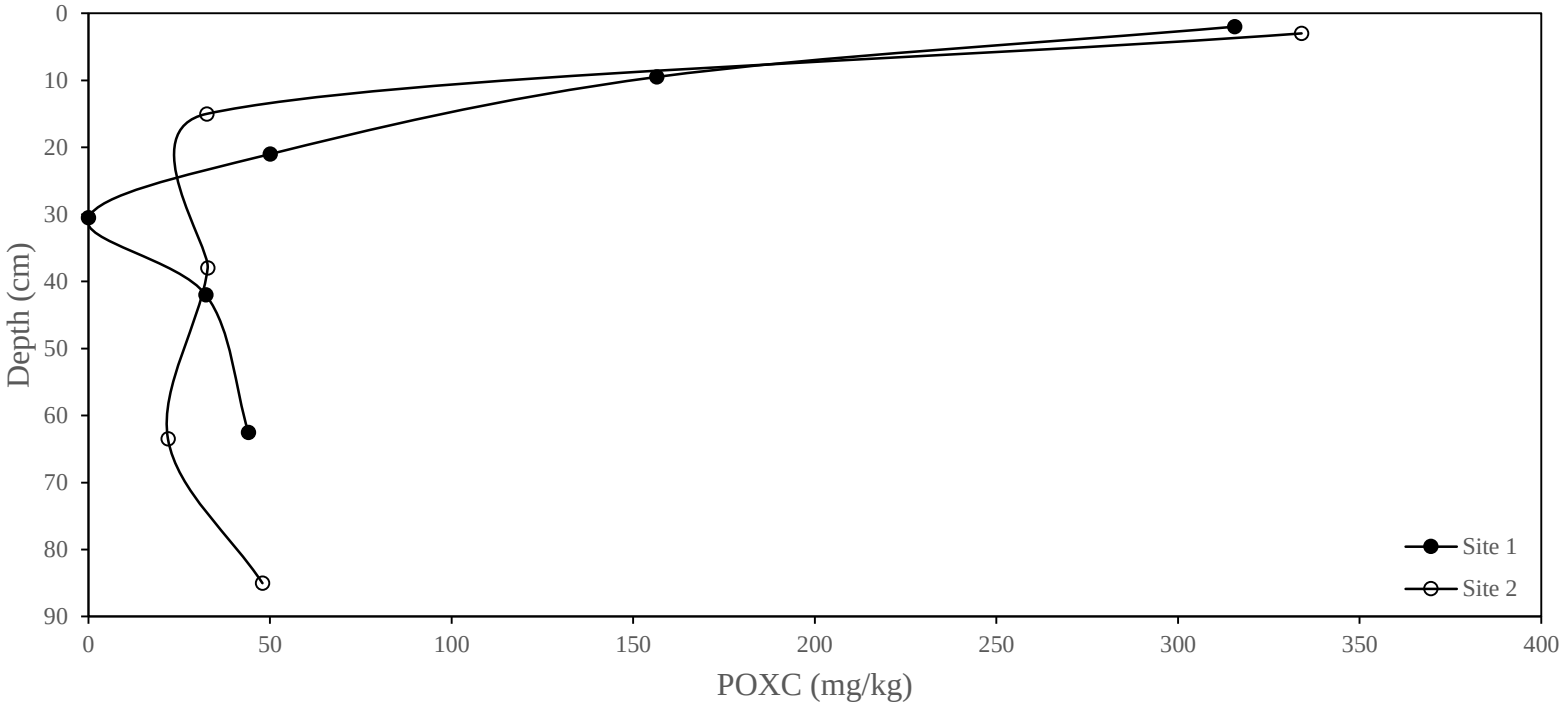


Figure 10. Concentration of permanganate-oxidizable carbon as a function of depth.

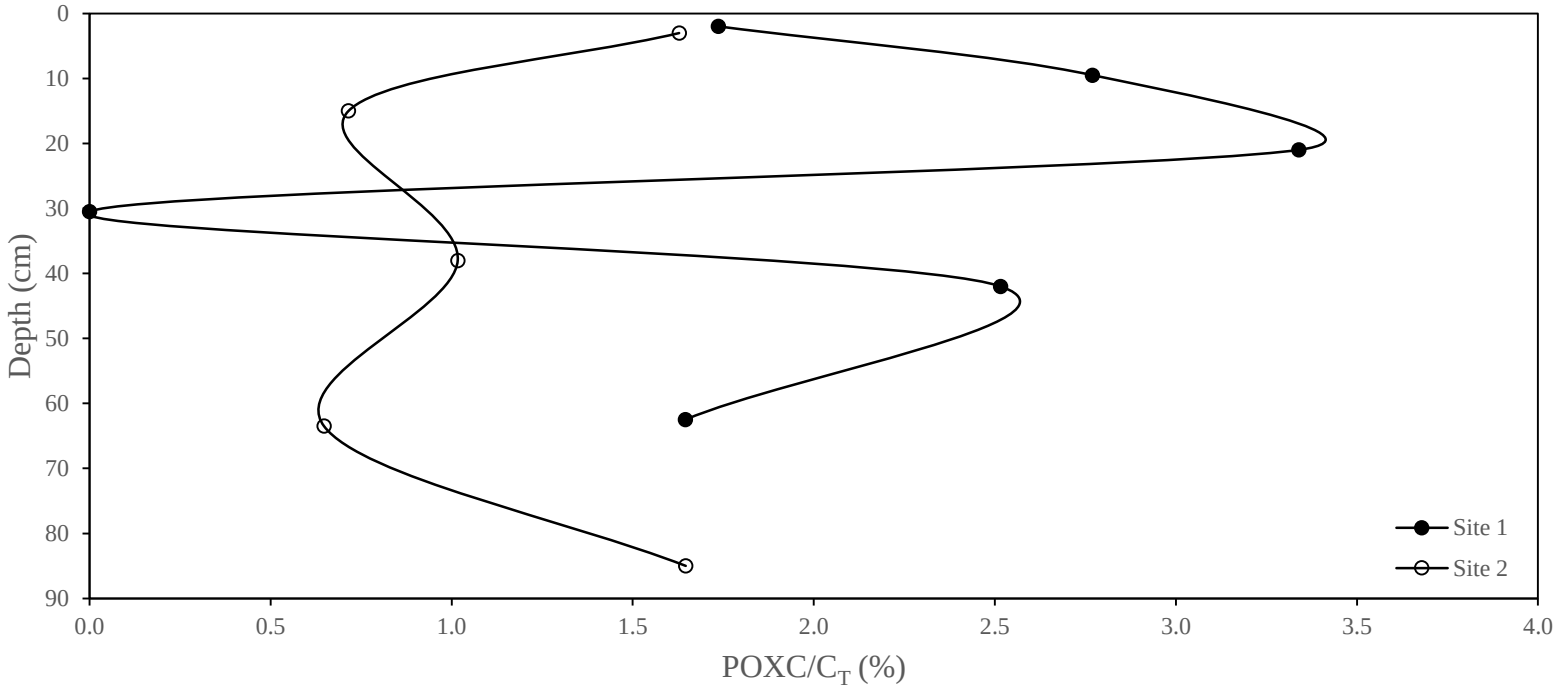


Figure 11. Comparison between study sites of POXC as a fraction of total carbon.

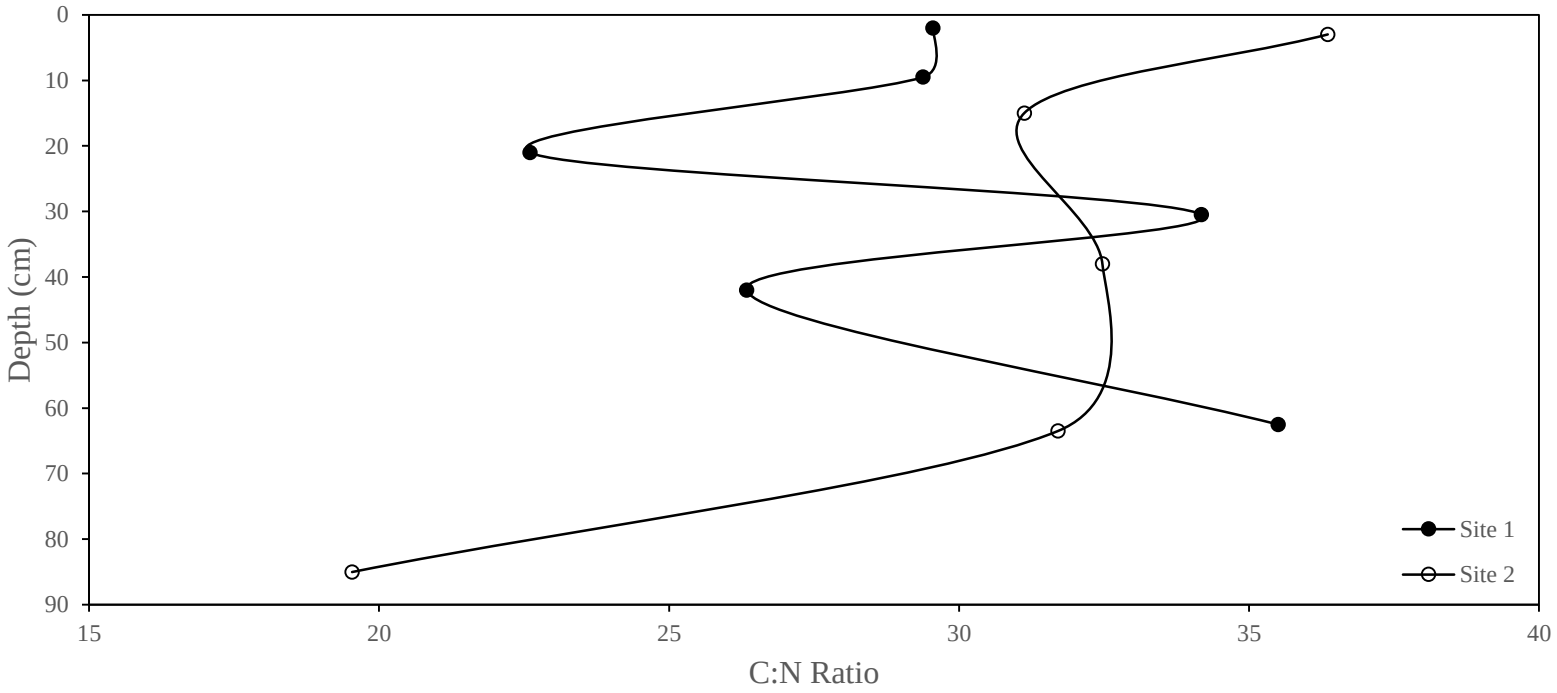
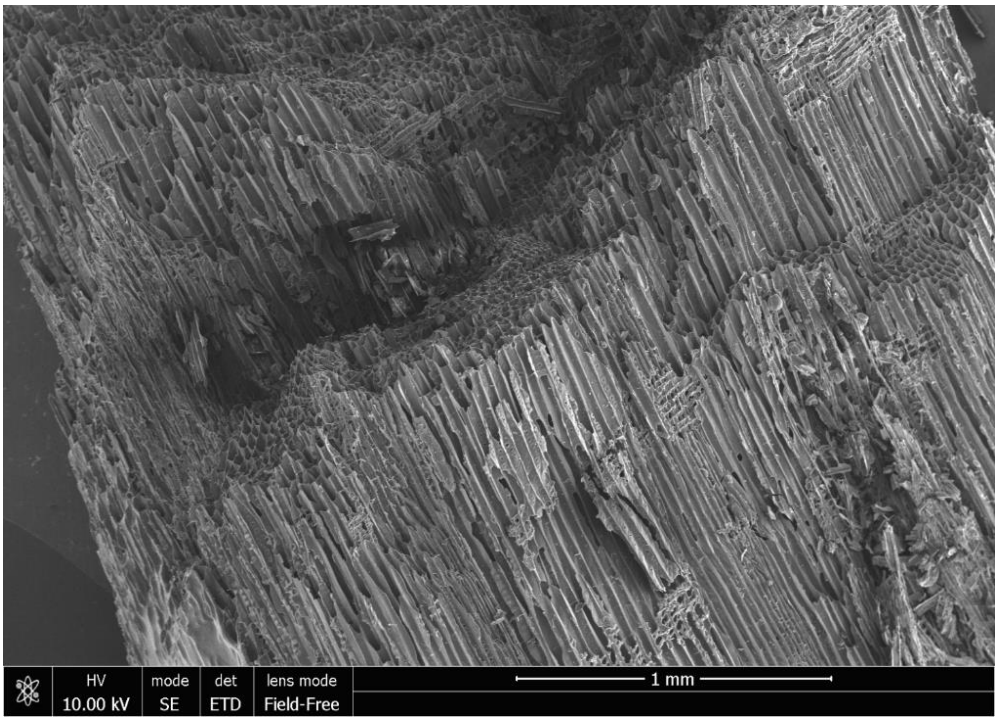


Figure 12. Comparison between study sites of carbon-to-nitrogen concentration ratios.

(a)



(b

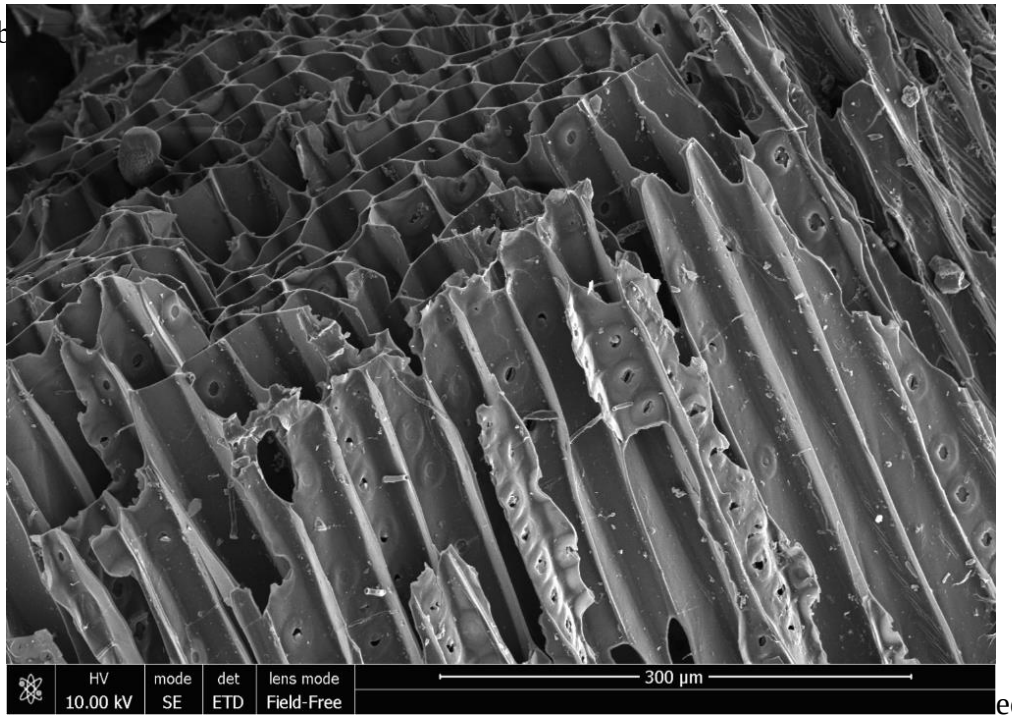


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Figure 13. Site 1 char specimen from the ground surface, above plant litter and rock fragments; (a) broad view; (b) enlarged area.

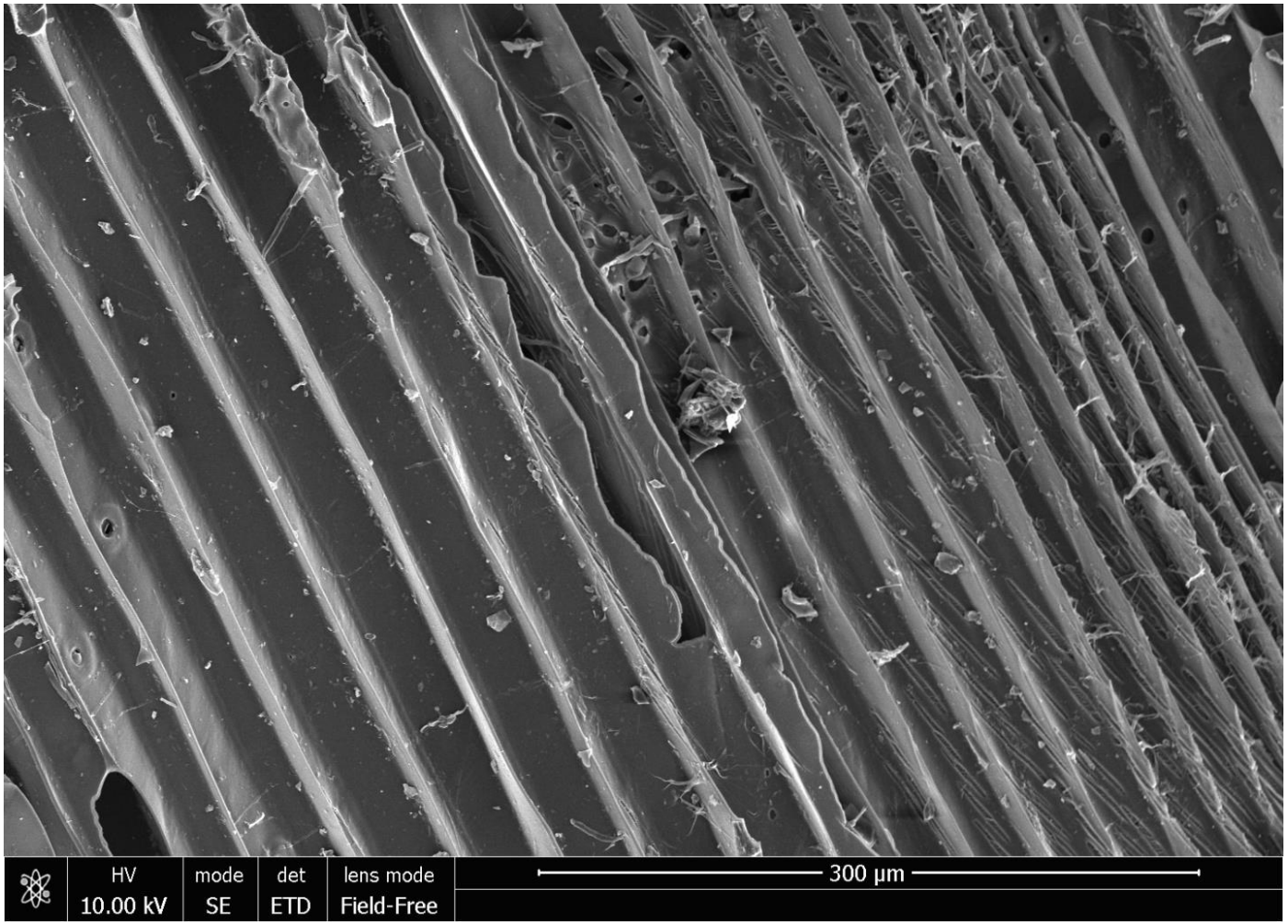
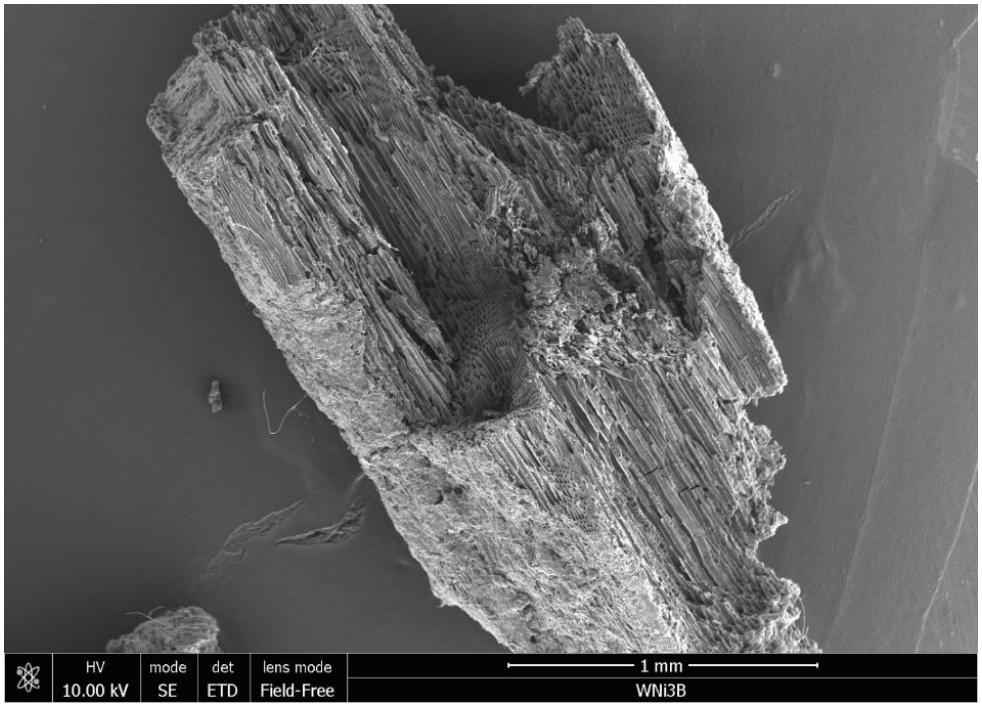


Figure 14. Site 1 char specimen from the ground surface, above plant litter and rock fragments.

(a)



(b)

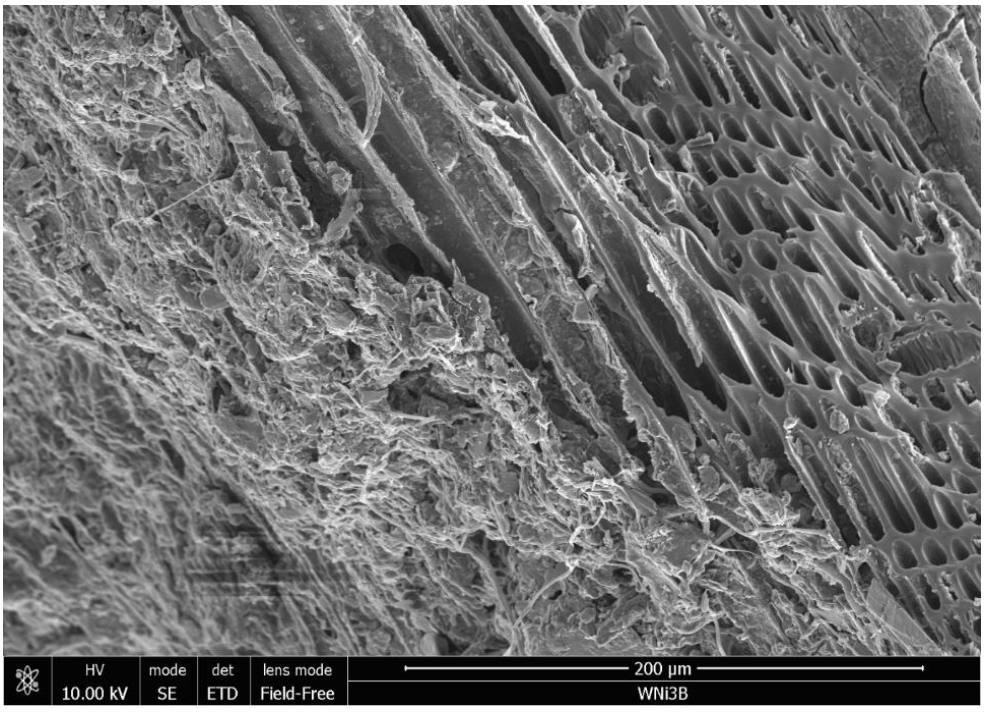


Figure 15. Site 2 char specimen from the ground surface, above plant litter and rock fragments; (a) broad view; (b) enlarged area.

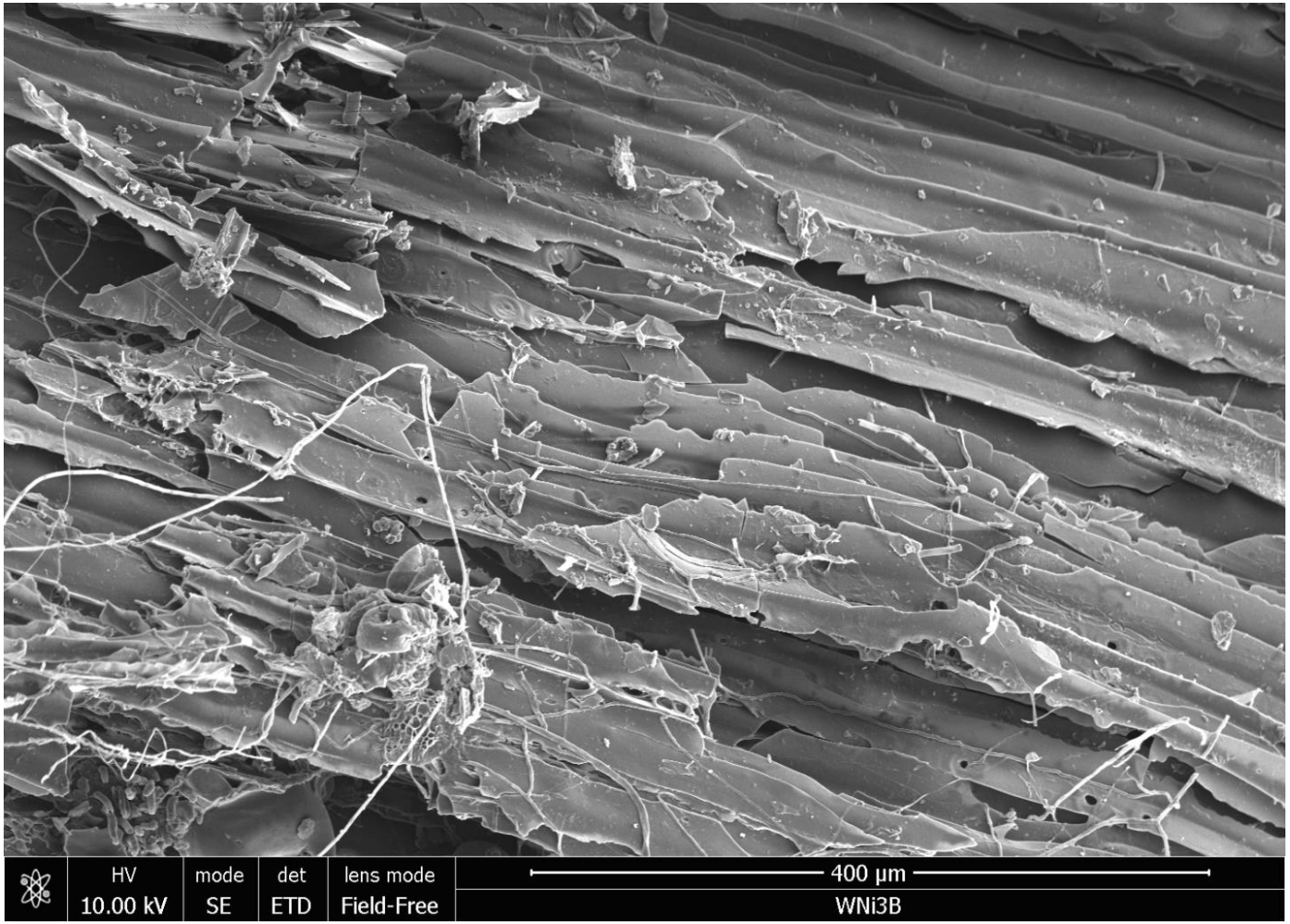
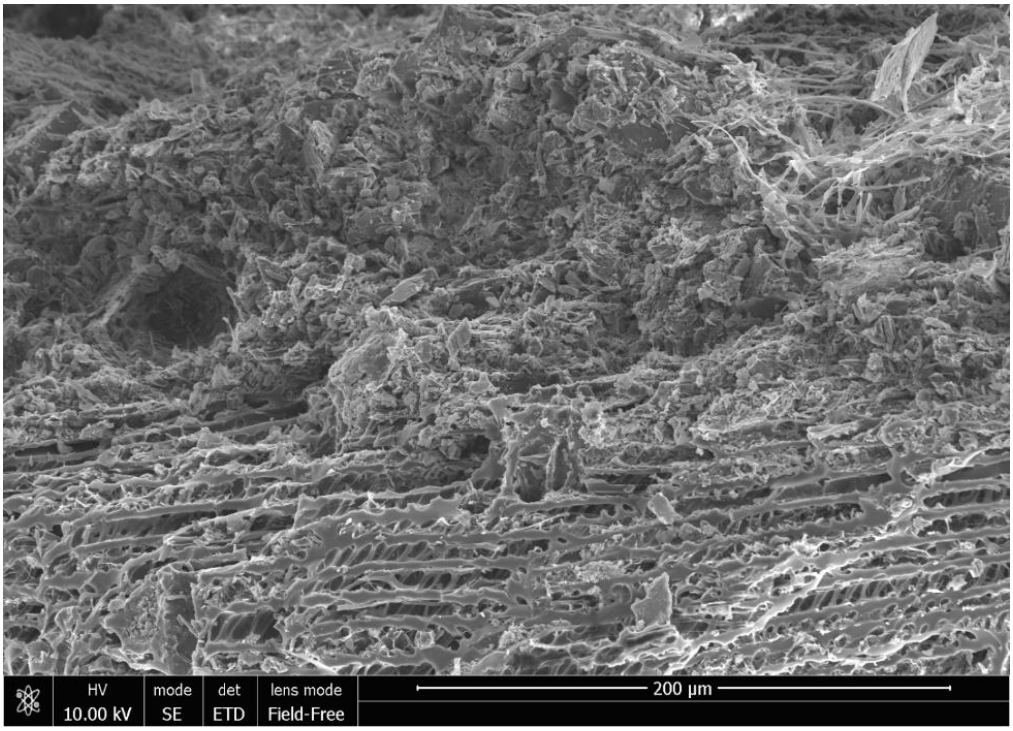


Figure 16. Site 2 char specimen from the ground surface, above plant litter and rock fragments.

(a)



(b)

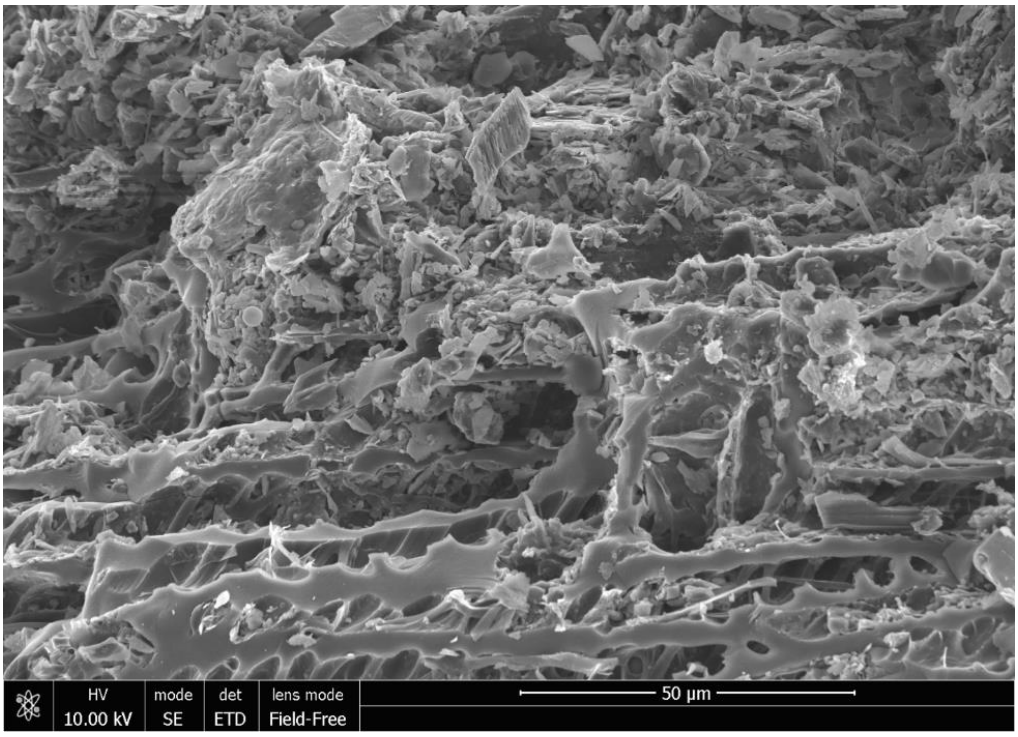


Figure 17. Site 1 char specimen from within a mineral soil Bt horizon, 27-34 cm; (a) broad view; (b) enlarged area.

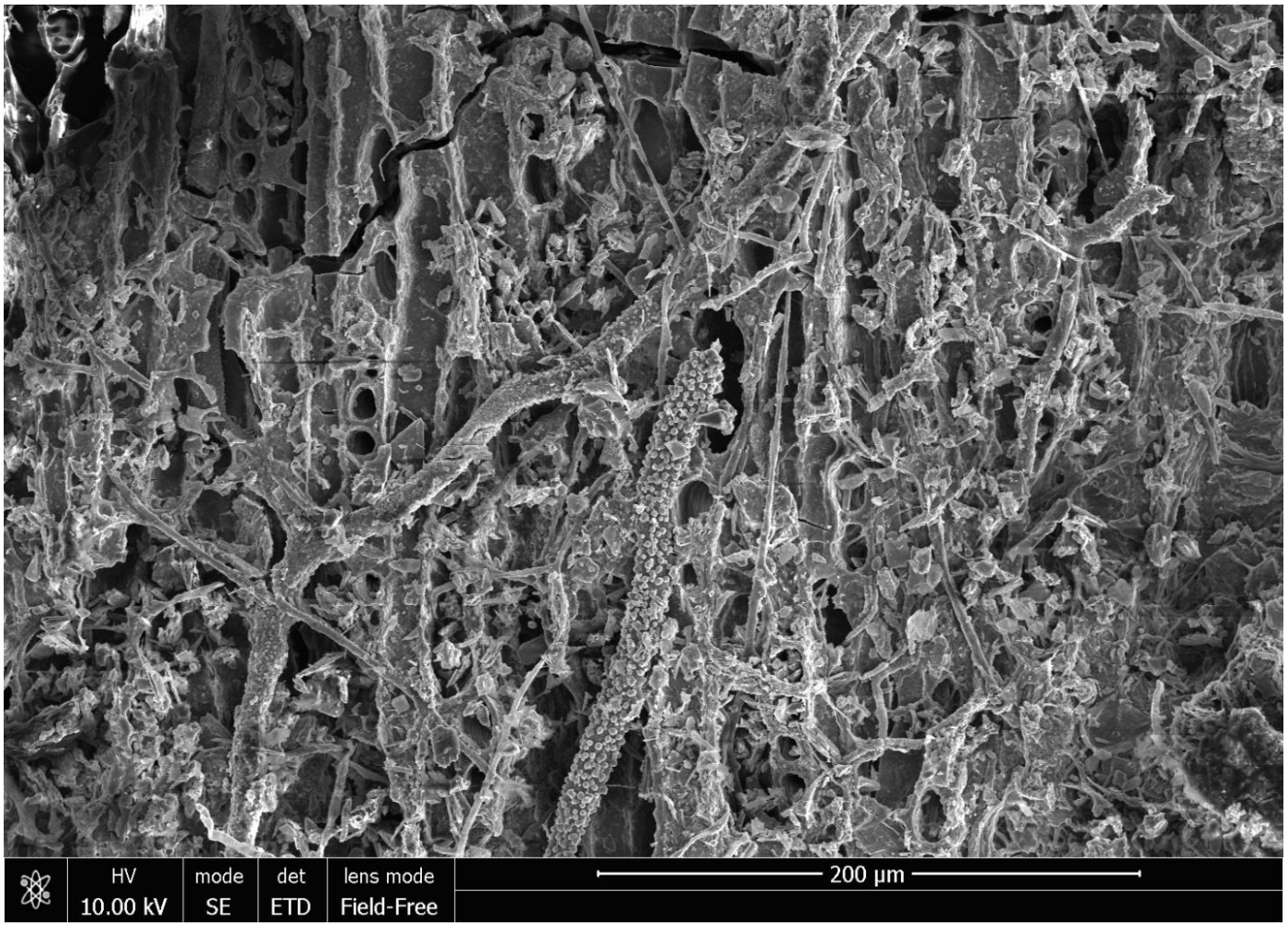
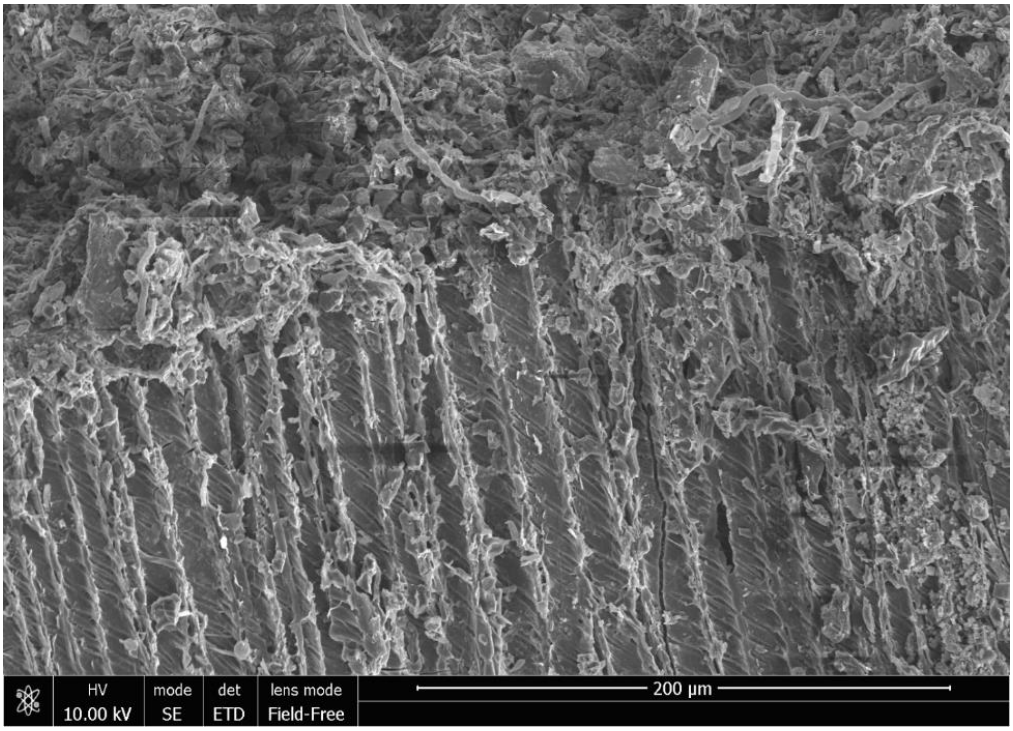


Figure 18. Site 1 char specimen from within a mineral soil Bt horizon, 27-34 cm.

(a)



(b)

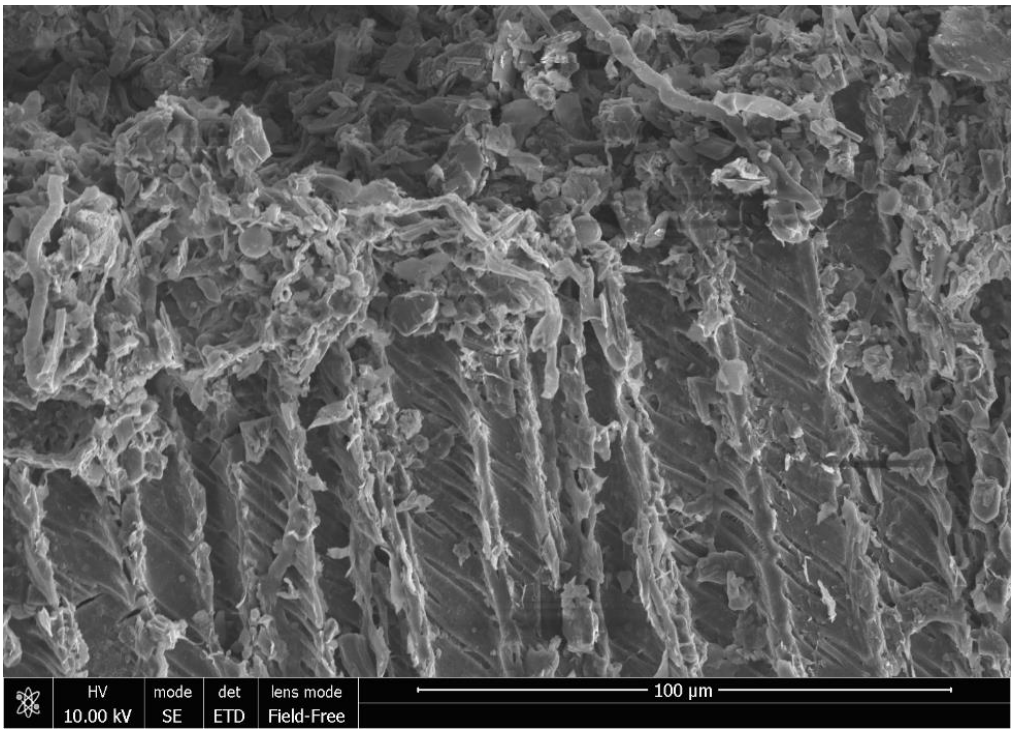


Figure 19. Site 2 char specimen from within a mineral soil Bt horizon, 24-52 cm; (a) broad view; (b) enlarged area.

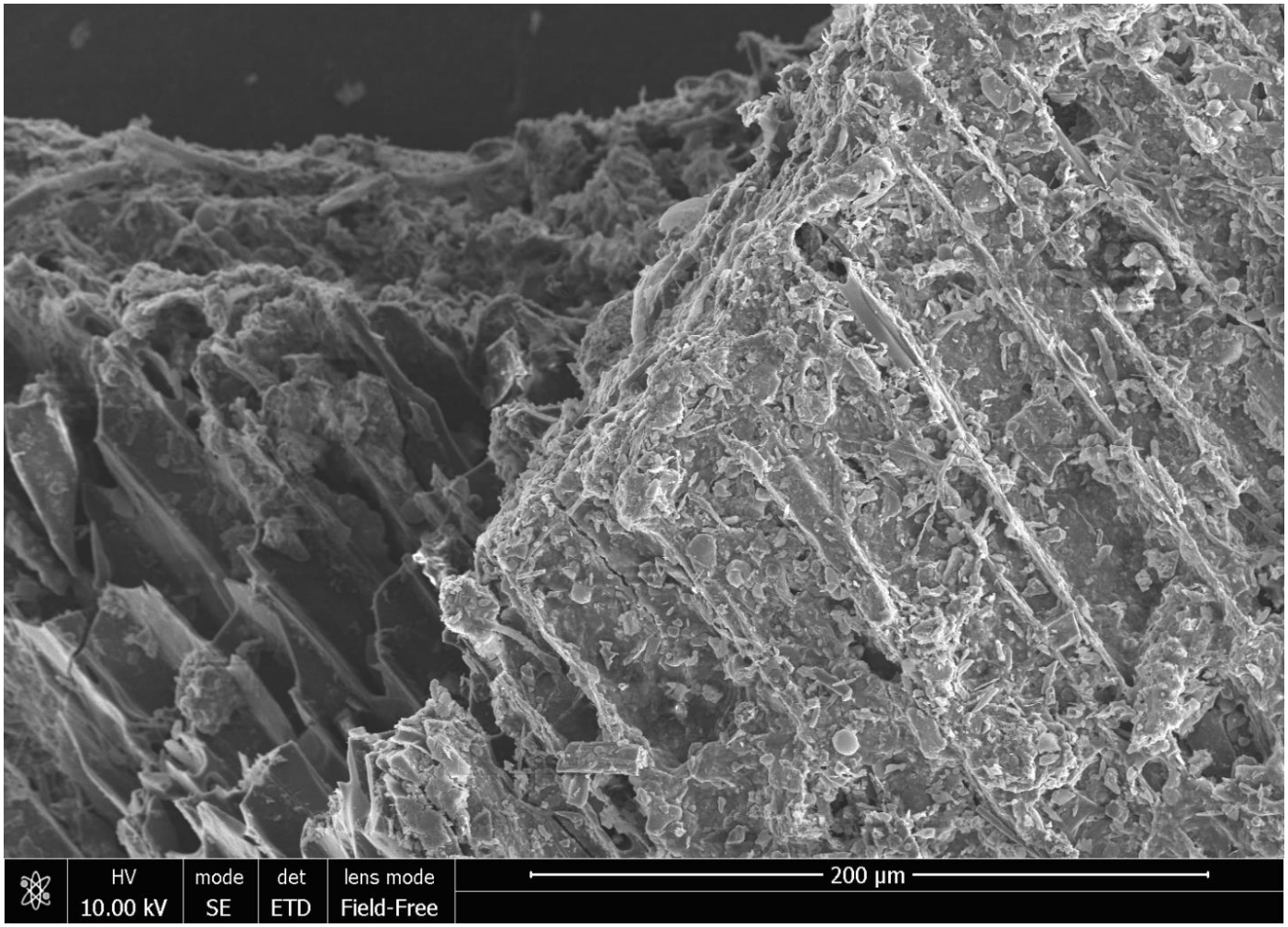


Figure 20. Site 2 char specimen from within a mineral soil Bt horizon, 24-52 cm.

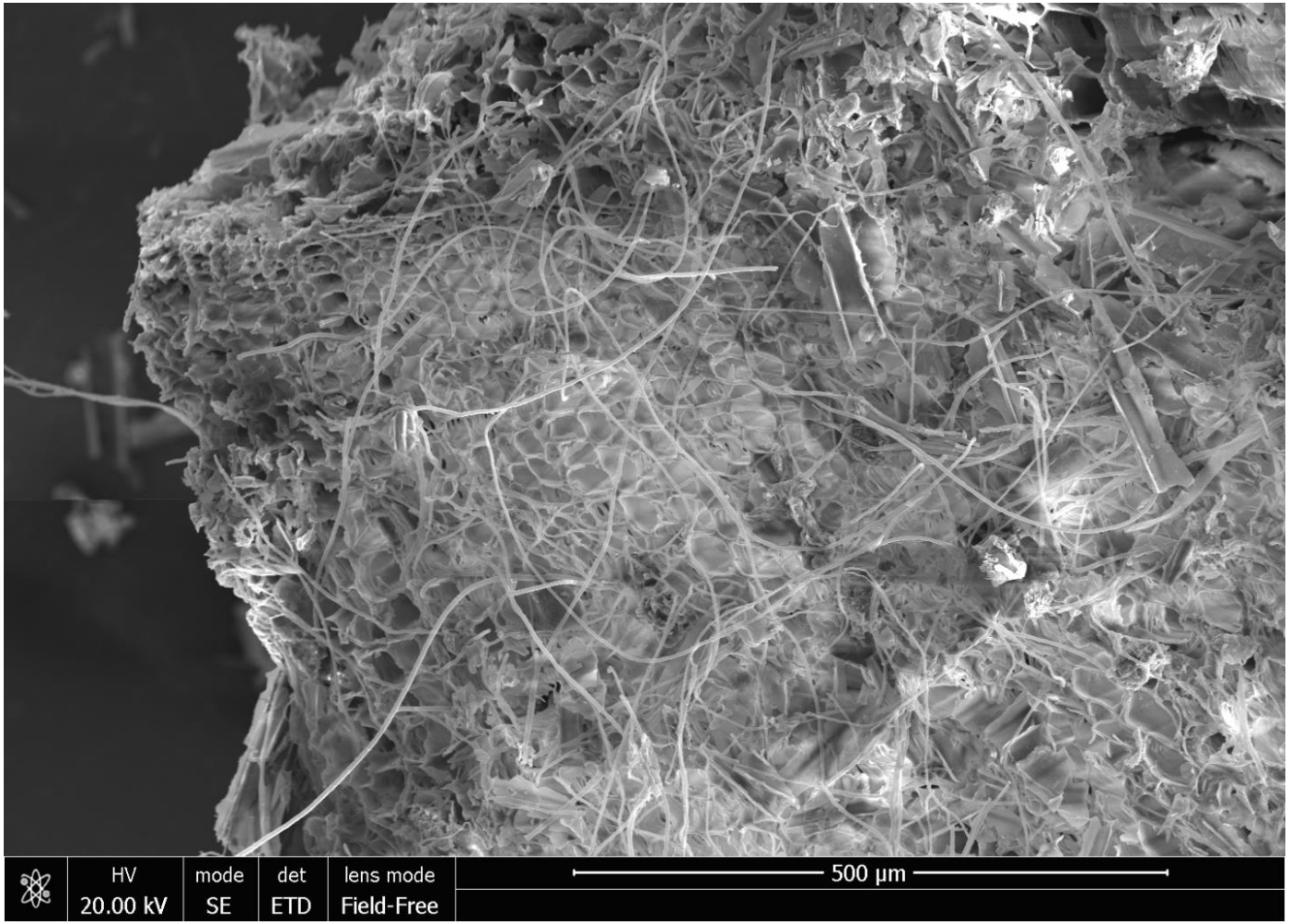


Figure 21. Site 1 char specimen from the soil surface, above mineral soil, below rock fragments.

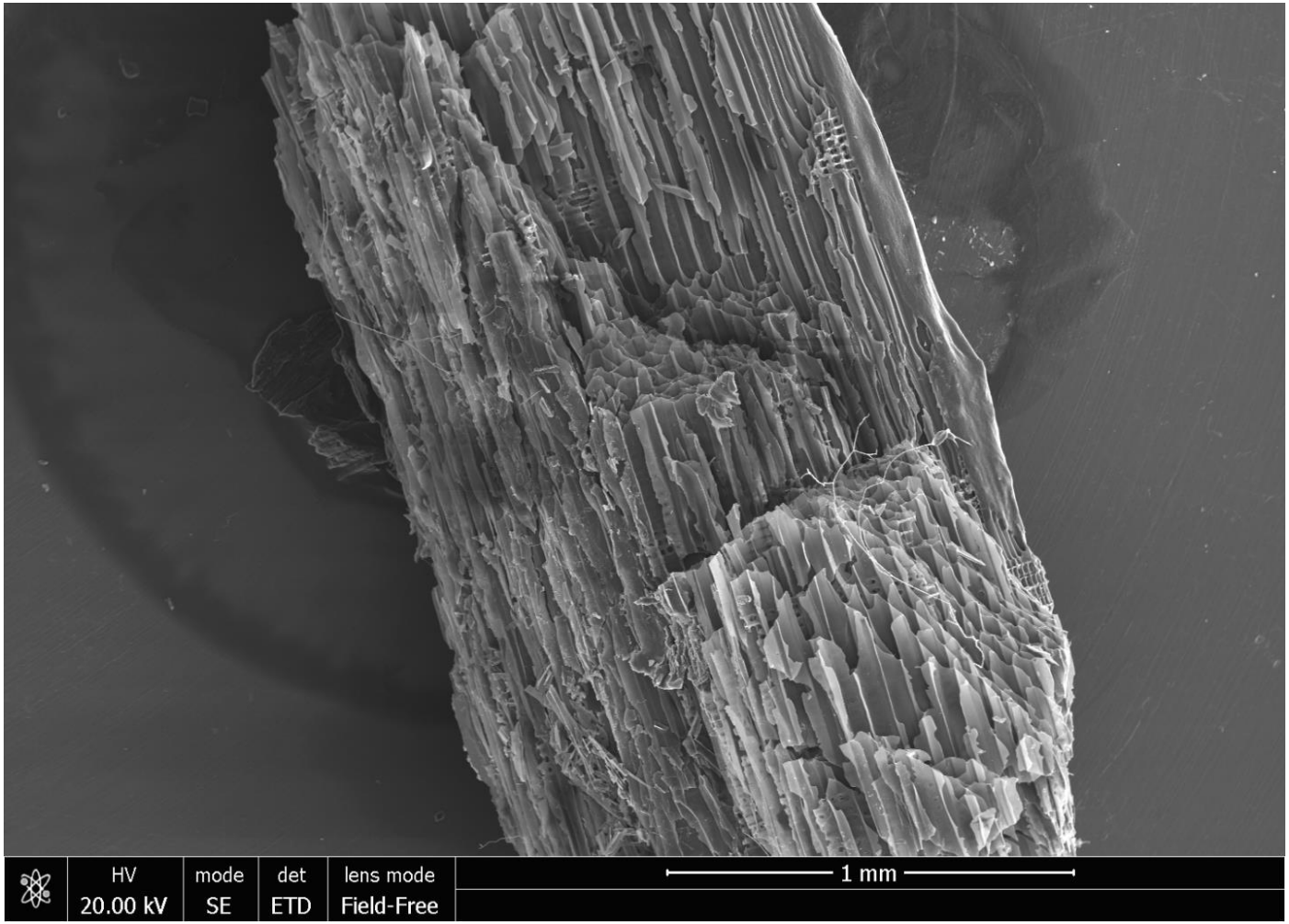
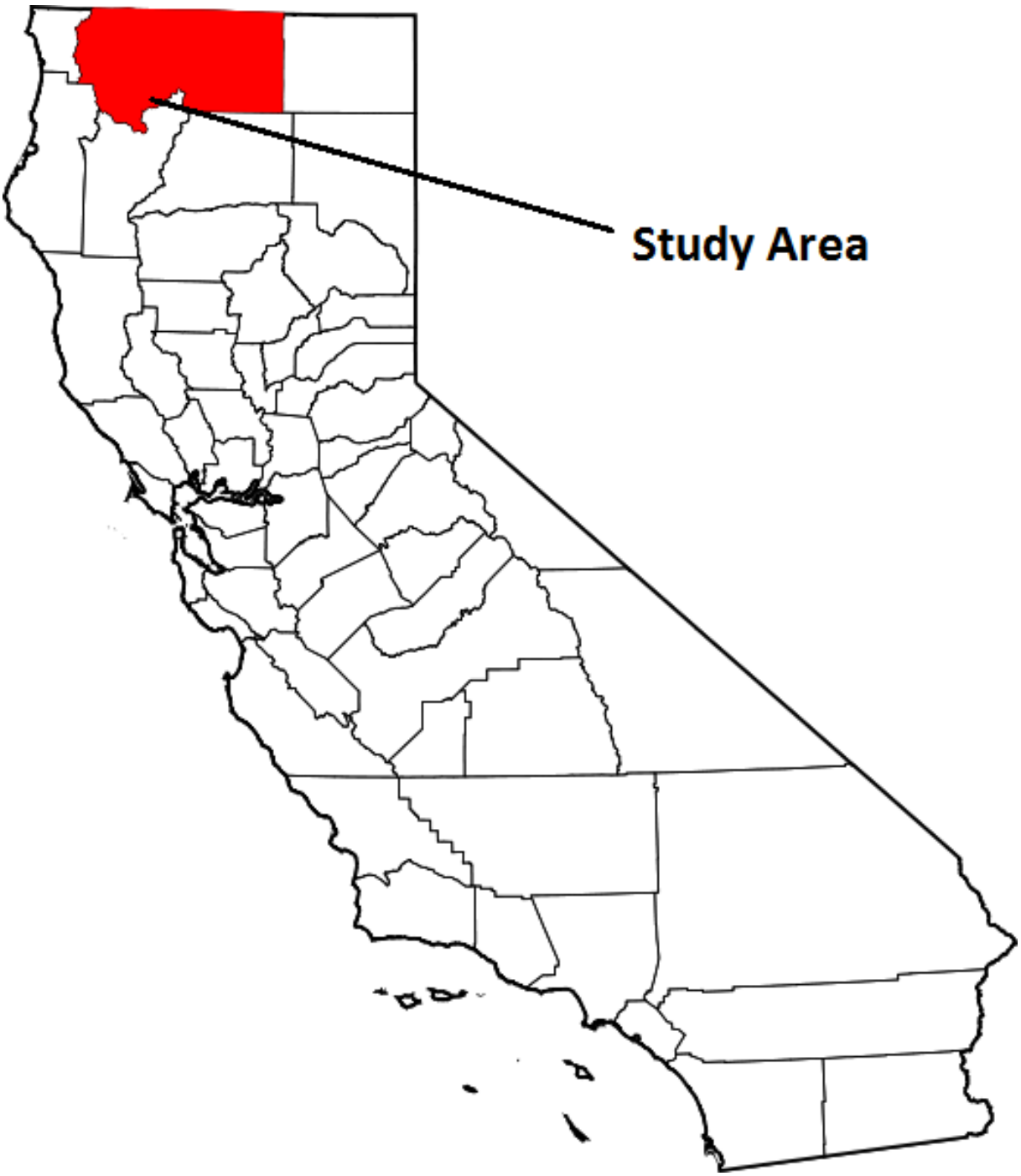
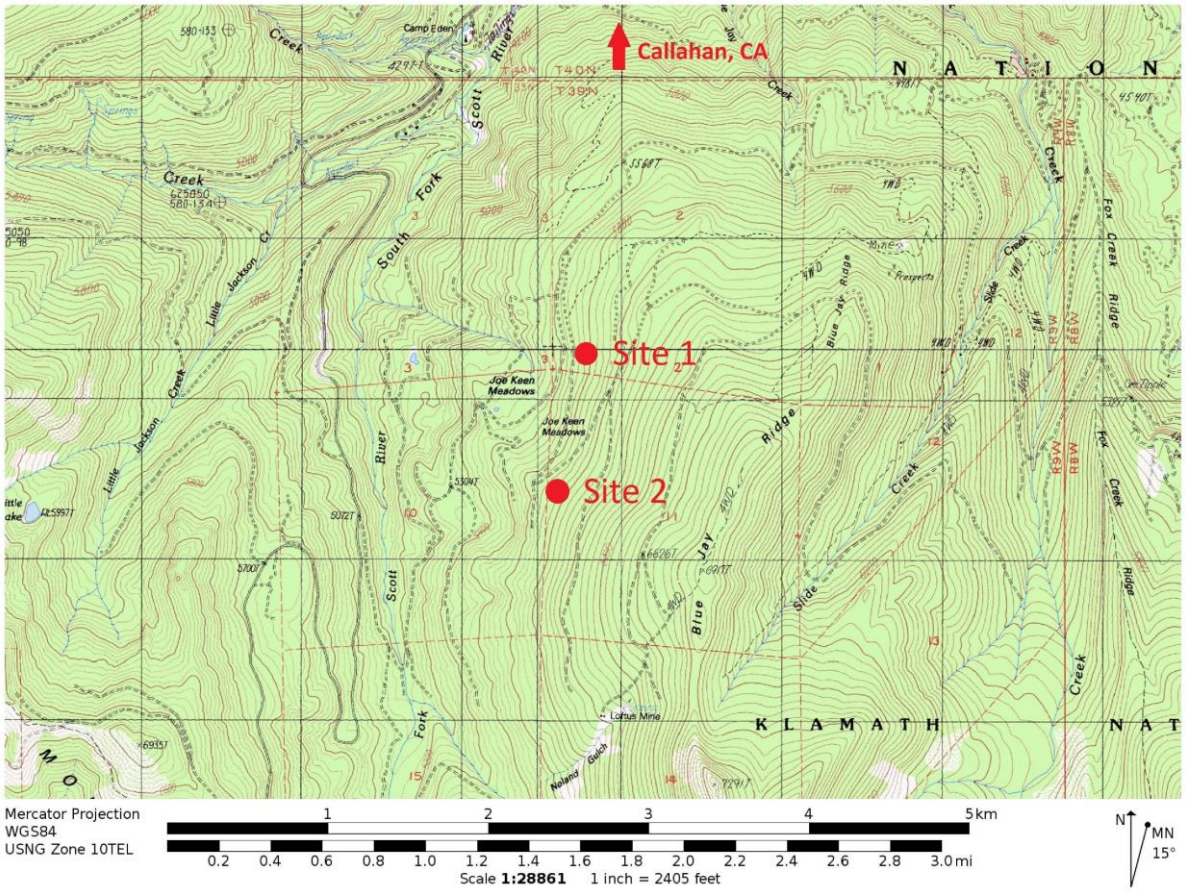


Figure 22. Site 1 char specimen from the soil surface, above mineral soil, below rock fragments.

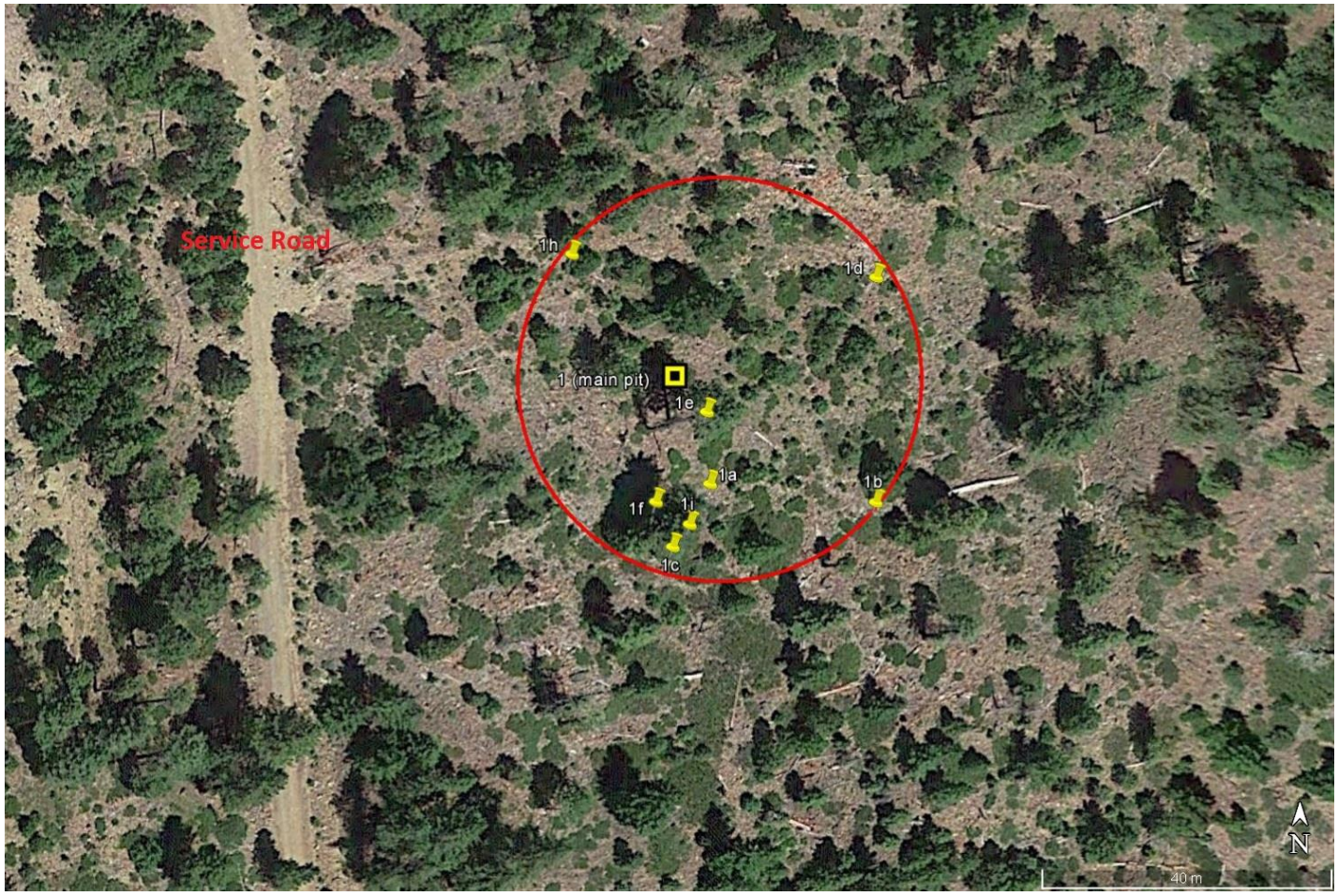
Appendix



Location of study area within Siskiyou county, California.



Topographic map of Blue Jay Ridge and location of study sites.



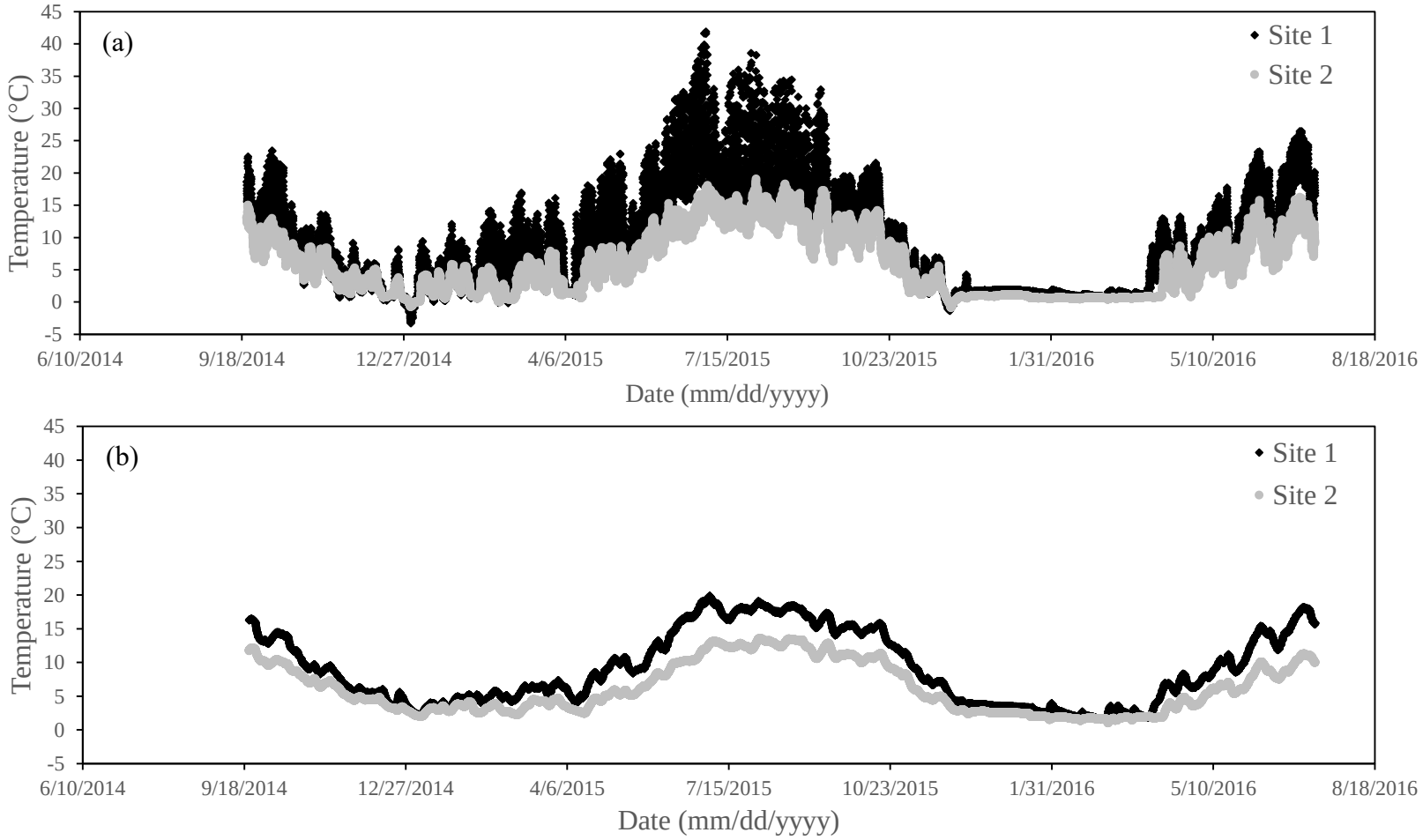
Aerial image of study perimeter and sampling points for Site 1.

Aerial image of study perimeter and sampling points for Site 2.

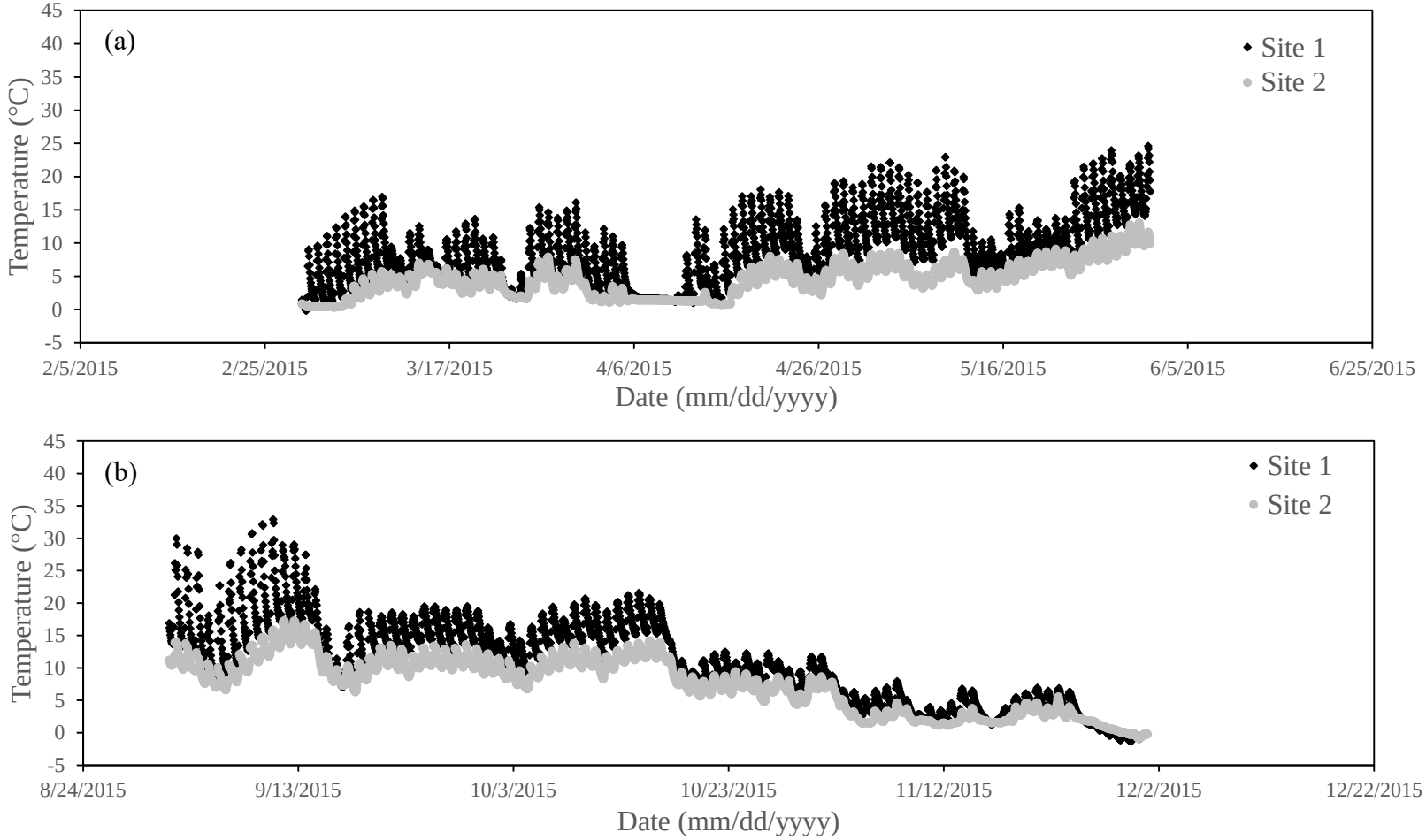
Detailed particle size distribution for all mineral soil samples.

Horizon	Depth	Particle size distribution†							
		Sand fractions					Total sand	Silt	Clay
		Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand			
	cm	%							
Site 1, main soil pit									
A	0-4	4.4	17	6.2	10.2	9.4	47.2	45.7	7.1
Bw	4-15	0	0	0.1	9.7	11.1	20.9	67.5	11.6
Bt1	15-27	0.3	11.6	4.8	10.7	9.8	37.2	53.8	9.0
Bt2	27-34	1.1	6.9	2.9	8.2	9.4	28.5	60.5	11.0
Bt3	34-50	1.5	8.9	6.1	8.7	8.8	34.0	55.6	10.4
BC	50-75+	0	0	1.3	10.7	11.1	23.1	66.8	10.1
Site 1, rep A									
A	0-12	5.5	18.3	3.5	9	8.6	44.9	46.9	8.2
Bw1	12-20	13.2	19.3	8.2	7.7	6.8	55.2	37.8	7.0
Bw2	20-33+	3.0	14.8	7.7	11.4	9.6	46.5	44.6	8.9
Site 1, rep B									
A	0-22	7.2	16.6	9.8	12.8	9.4	55.8	38.2	6.0
Bw	22-42+	8.8	21.4	9.3	12.4	8.4	60.3	34.1	5.6
Site 1, rep C									
A	0-24	5.2	15.2	9.1	13.7	9.6	52.8	39.8	7.4
Bt1	24-36	14.3	17.3	9.3	9.6	8	58.5	35.1	6.4
Bt2	36-56+	5.7	14.6	7.6	12.3	9.4	49.6	42.8	7.6
Site 1, rep D									
A	0-21	5.1	17.2	6.8	11.7	9.9	50.7	42.3	7.0
Bt	21-41+	0.0	0.0	0.0	10.9	12.6	23.5	64.8	11.7
Site 2, main soil pit									
A1	0-6	0	3.4	2.9	14.9	11.2	32.4	58.9	8.7
Bw	6-24	0.2	6.6	7.3	12.7	10.3	37.1	54.6	8.3
Bt1	24-52	1.6	9.8	10	12.7	9.4	43.5	48.6	7.9
Bt2	52-75	0.0	2.8	2.1	11.8	11.2	27.9	63.7	8.4
BC	75-95+	0.0	1.3	4.4	9.4	11.6	26.7	66.6	6.7
Site 2, rep A									
A	0-14	0.0	1.1	3.1	13.1	10.7	28.0	62.4	9.6
Bw	14-35+	0.0	7.3	7.4	10.8	9.2	34.7	56.5	8.8
Site 2, rep B									
A	0-8	2.9	12.1	8	13.7	9.5	46.2	46.4	7.4
Bt	8-32+	0	2.7	3.9	13	9.2	28.8	60.0	11.2
Site 2, rep C									
A	0-15	0.9	9.3	9.1	14.1	9.7	43.1	49.5	7.4
Bw	15-35+	3.1	9.5	7.2	13.4	9.6	42.8	49.1	8.1
Site 2, rep D									
A	0-5	0	0	0.1	10.4	9.3	19.8	68.9	11.3
Bw	5-19	0	0.6	3.6	11.7	10.7	26.6	63.7	9.7
Bt	19-39+	0	0	0.9	10	9.5	20.4	68.3	11.3

†Particle sizes are based on USDA-NRCS classification.



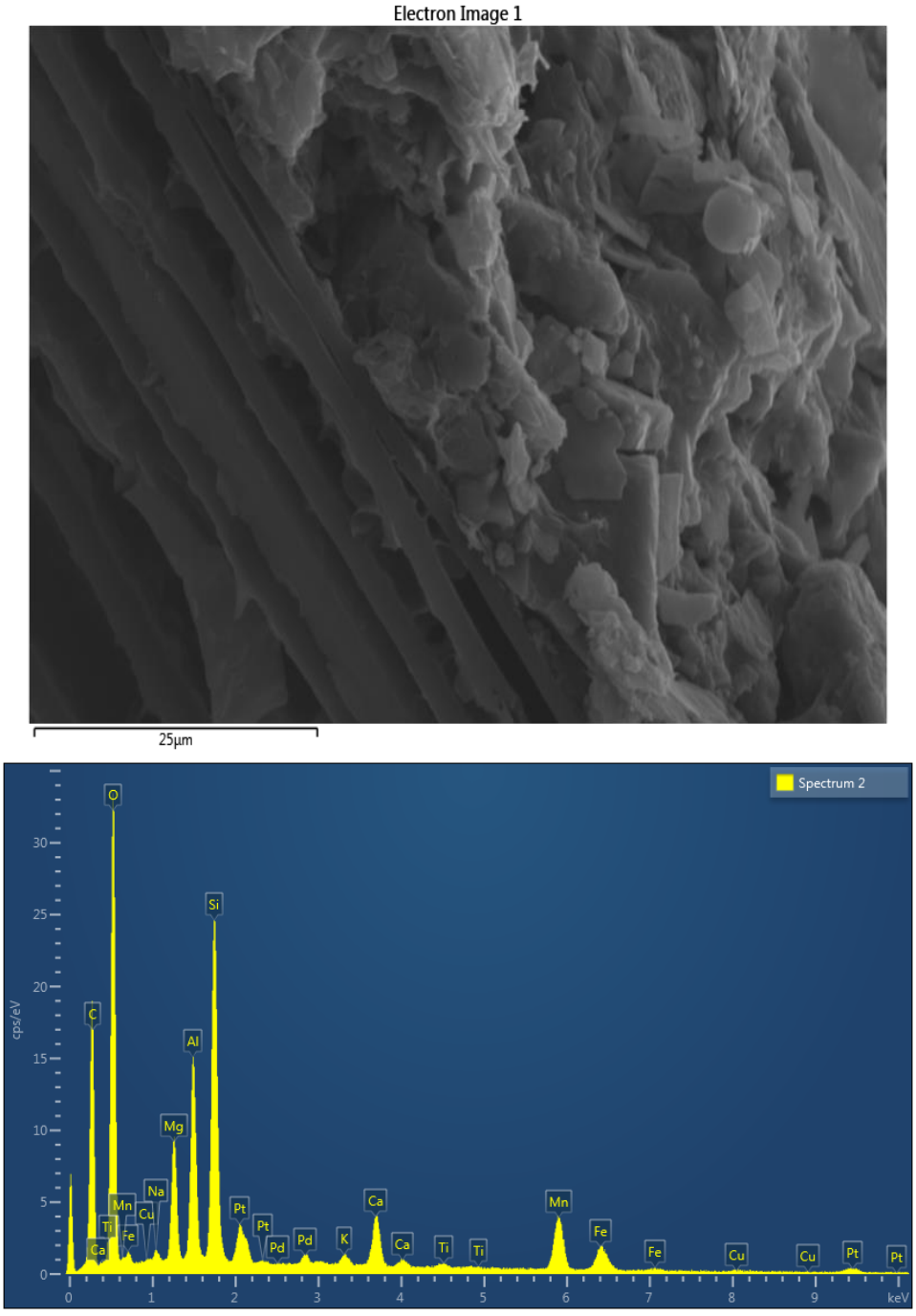
Supplement to Figure 3 showing the full temperature record (a) directly below the RF/O horizon, and (b) at 50 cm below mineral soil surface.



Supplement to Figure 4 showing soil surface (directly below RF/O horizon) temperature for (a) March, April, May, and (b) September, October, November.

Carbon, nitrogen, and permanganate-oxidizable carbon (POXC) measurements for mineral soil samples.

Horizon	Carbon		Nitrogen		C:N ratio	POXC	
	%	Conc.	%	Conc.		Conc.	% of total carbon
		mg kg^{-1}		mg kg^{-1}		mg kg^{-1}	
Site 1, main soil pit							
A	1.82	18181.3	0.06	615.23	29.6	315.6	1.74
Bt1	0.57	5651.3	0.02	192.36	29.4	156.5	2.77
Bt2	0.15	1498.8	0.01	66.31	22.6	50.1	3.34
Bt3	0.10	990.9	0.00	28.99	34.2	0.0	0.00
Bt4	0.13	1286.8	0.00	48.86	26.3	32.4	2.52
BC	0.27	2679.6	0.01	75.48	35.5	44.1	1.65
Site 1, rep A							
A	1.06	10576.4	0.04	383.62	27.6	135.2	1.28
Bw1	0.61	6083.0	0.02	237.53	25.6	94.9	1.56
Bw2	0.25	2453.9	0.01	109.62	22.4	62.3	2.54
Site 1, rep B							
A	1.93	19296.8	0.07	664.95	29.0	293.6	1.52
Bw	0.68	6811.1	0.04	353.86	19.2	100.2	1.47
Site 1, rep C							
A	1.81	18146.9	0.07	669.86	27.1	360.5	1.99
BA	0.64	6358.7	0.04	405.82	15.7	65.7	1.03
Bw	0.61	6072.1	0.03	347.70	17.5	57.9	0.95
Site 1, rep D							
A	3.05	30454.3	0.08	769.92	39.6	320.4	1.05
Bt	0.56	5590.0	0.02	246.69	22.7	88.0	1.57
Site 2, main soil pit							
A1	2.05	20508.2	0.06	564.04	36.4	334.0	1.63
BA	0.46	4563.8	0.01	146.62	31.1	32.6	0.72
Bw1	0.32	3234.7	0.01	99.61	32.5	32.9	1.02
Bw2	0.34	3391.3	0.01	106.97	31.7	22.0	0.65
BC	0.29	2912.9	0.01	149.12	19.5	48.0	1.65
Site 2, rep A							
A	2.34	23379.1	0.07	662.46	35.3	316.9	1.36
Bw	0.51	5116.1	0.02	223.19	22.9	102.3	2.00
Site 2, rep B							
A	1.90	18956.9	0.07	651.95	29.1	347.3	1.83
Bt	0.91	9064.1	0.05	467.18	19.4	149.8	1.65
Site 2, rep C							
A	1.52	15174.8	0.04	433.06	35.0	146.1	0.96
BA	0.70	7006.4	0.04	382.67	18.3	125.2	1.79
Site 2, rep D							
A	1.98	19802.4	0.07	743.08	26.6	530.2	2.68
Bw1	0.62	6186.8	0.03	328.87	18.8	116.9	1.89
Bw2	0.37	3656.9	0.02	223.43	16.4	14.6	0.40



Example figure of EDX spectra and related image area.