

THE EFFECTS OF HISTORIC CHARCOAL PRODUCTION ON SOIL MORPHOLOGY AND GEOCHEMISTRY IN NORTHWESTERN CONNECTICUT

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INTRODUCTION

From the mid-1700s until the early 1900s, colliers clear-cut much of the forested landscape of northwestern Connecticut to support the local iron industry. After the harvested timber was transported to charcoal hearth sites, wood was pyrolyzed to produce charcoal. This process introduced a distinct set of anthropogenic disturbances on hillslopes in the region and is likely to have affected the forest ecosystem (e.g., Young et al., 1996).

Based on results of LiDAR analysis, at least 20,500 relic charcoal hearths (RCH) remain in Litchfield County, Connecticut today (Johnson et al., 2015). During production, each of these hearths, (approximately 70-125 m² in size), held up to 50 cords (180 m³) of wood that were covered in soil and fired at temperatures reaching 450°C (Young et al., 1996). Then, over the course of 14 days, the wood slowly carbonized to charcoal. Production at each site continued until the adjacent timber supply was exhausted, after which the colliers would move sites, only to return every 20-30 years once the surrounding landscape had reforested (Mikan and Abrams 1995).

Over time, this cycle of repetitive disturbances had a significant long-term effect on many chemical and morphological components of soils in and around RCHs (Mikan and Abrams 1995; Young et al., 1996; Tryon 1948). Today, the full effects of charcoal production are still not well understood. Previous studies (Borchard 2014; Nigussie and Kissi 2011; Ogundunde and Fosu 2004; Hart et al., 2008; Young et al., 1996) have focused mainly on one dimension of change, comparing soil properties in RCH sites

to non-RCH sites; very few studies have addressed trends of lateral or vertical soil changes in RCH site environments. This study aims to more closely examine the chemical and morphological differences between RCH and non-RCH soils and also to assess the impacts of charcoal production up to 30 m lateral distances away from individual RCH sites and up to 70 cm depth (determining changes within the vertical soil profile).

METHODS

Study Site

This study was conducted in the Housatonic and Mohawk State Forests in Litchfield County, Connecticut (Fig. 1). Litchfield County is located in the Northwest Highlands region of the state. Average temperature ranges from -6° C in winter to 18° C in the summer; average precipitation ranges from 111 to 137 cm per year, and the average relative humidity is approximately 50%. Much of the area is steeply sloped, and the elevation ranges from 100 to 720 meters above sea level (Faber 2008)

The Northwest Highlands region was shaped by the last advance of the Laurentide ice sheet and comprises till plains and drumlins underlain by Proterozoic and early Paleozoic metamorphosed sedimentary and igneous rocks (Litchfield County Soil Survey). The soil, which formed in glacial till and glaciofluvial deposits, is classified as a Stockbridge loam (Faber 2008). More recently, in the late 1700s, this region was cleared and cultivated for the region's historic and extensive agricultural and charcoal industries (Foster et al., 1998). In the early 1900s these industries

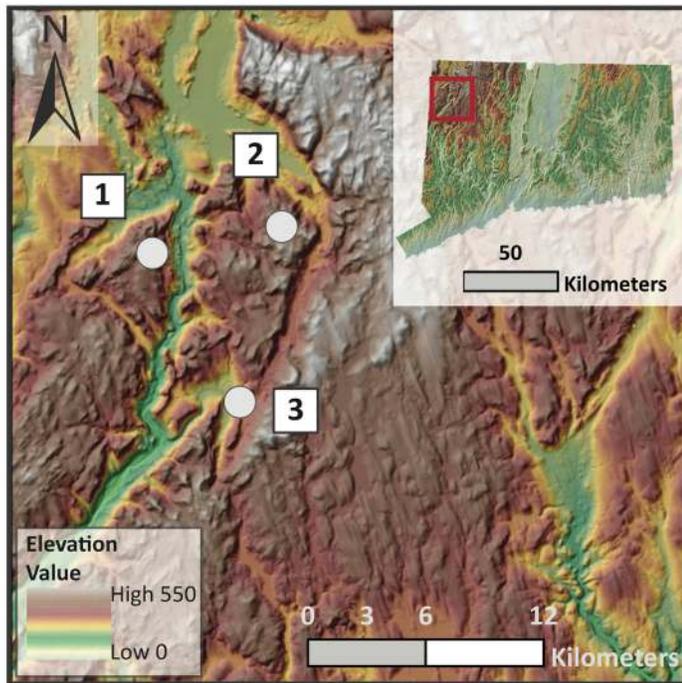


Figure 1. 1m LiDAR DEM map highlighting study areas where RCH transect, AS, and vertical profile samples were collected. Site 1: Housatonic State Forest, Sharon, CT; Site 2: Housatonic State Forest, Cornwall, CT; Site 3: Mohawk State Forest, Cornwall CT. Inset map shows Connecticut, noting Litchfield County in the northwest highlands region of the state.

declined and the region reforested (Mikan and Abrams 1995).

Soil Sampling

RCH sites were located using 1m LiDAR DEM data and selected for soil sampling. At three RCH sites, we used a cylindrical tulip bulb planter with a penetration depth of 15 cm and volume of 498 cm³ to sample and measure charcoal depth. Samples were collected from the top 15 cm of the soil profile along two randomly directed transects measuring 0, 2, 5, 10, 20, and 30 meters from the RCH center (Fig. 2). For comparison between RCH and adjacent non-RCH sites, we assumed an approximate RCH radius of 5 m. Samples collected within the 5 m radius of the RCH center (e.g., 0, 2, 5 m) were defined as RCH samples. Samples collected beyond the 5 m radius (10, 20, 30 m) were referred to as adjacent site (AS) samples. Some sites were larger or smaller than 5 m and the RCH sites were not perfectly circular. Therefore the RCH-AS boundary is variable and may not accurately represent all samples and their placement relative to the center of a RCH.

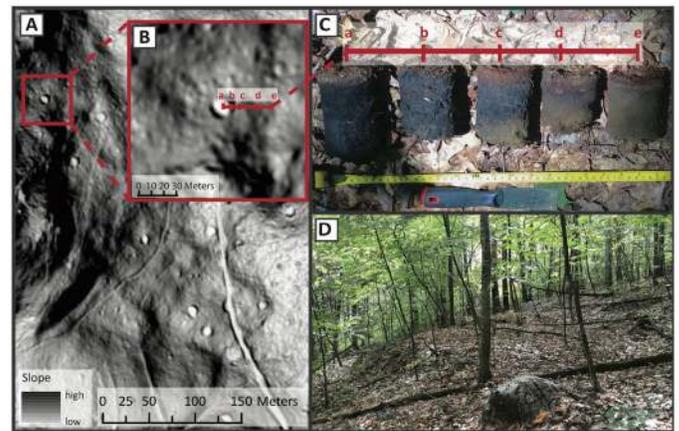


Figure 2. Example RCH location and transect. (A) LiDAR DEM hillshade image of RCHs on a hillslope. The RCH is characterized by a light grey indented circle. (B) Zoom in on the selected RCH site, showing an example 30-meter transect. Red letters indicate specific sample locations along the transect. (C) Example soil samples. From left to right, samples display a decrease in charcoal thickness with an increase in distance from RCH center. Samples a-e were taken 0, 2, 5, 10 and 20 m from RCH center, respectively. The final transect sample, at 30 m from RCH center, is not photographed. (D) Field photo of a RCH site today.

In addition, seven vertical soil pits were dug and profiles analyzed. Five were located in RCH sites and two were control sites (CS), located in regions of no charcoal production. Despite the absence of charcoal production, the CS soils were not undisturbed; like most of Connecticut, these sites had previously been cleared of forest for agriculture. They were therefore representative of soils beyond that of RCH sites. In every profile, samples were taken at either 5 or 10 cm intervals, starting beneath the O horizon and reaching an approximate depth of 1 m. Samples were dried for 12 hours at 80°C.

Soil Properties

Charcoal (Ac) thickness was defined in the field by color and charcoal content. Ac layers had a consistent ashy black color with abundant charcoal fragments (Fig 2.). Using the standard volume of the bulb planter, bulk density was determined as the quotient of sample weight and volume. Organic content was determined by Loss on Ignition (LOI). Following Dean (1974), 10 g of soil was extracted and burned at high temperature (550 °C) for 3 hours. The remainders of samples were sieved for chemical analysis, and

the mass percent of each grain size category (>2 mm, 2 mm-150 μ , <150 μ) was recorded. Extractable phosphorus was determined using colorimetry. 1 gram of air-dried, >2 mm soil was combined with 10 ml of 0.025 N HCL and 0.03 N NH₄F (the Bray-1 extractant) and shaken for 5 minutes. The sample was then treated with a molybdate-ascorbic acid reagent, and the intensity of the blue color developing in the filtrate was determined using a Brinkman PC 900 probe colorimeter at 880 nm. Exchangeable Ca²⁺, K⁺, Mg²⁺, and Na⁺ concentrations were analyzed using an Inductively Coupled Atomic Emission Spectrophotometer (ICP-AES) at the University of Minnesota. 3 g of air-dried >2 mm soil was combined with 30 ml of 1M NH₄OAc for 30 minutes. The extracts were then centrifuged and the supernatant was decanted and analyzed by ICP-AES. Soil pH was measured using a Mettler Toledo Seven-Multi pH meter with in InLab Pro combination electrode. These values were uncharacteristically low for the Stockbridge series, which are only slightly acidic (pH of 6.1 to 6.5) (Litchfield County Soil Survey). Our samples ranged from strongly to extremely acidic (pH of 3.7 to 5.2) and had no significant ($P > 0.05$) difference between sample sites. This suggests systematic error in sample collection or storage.

Statistical Analyses

The mean properties of soils between AS and RCH sites were compared by an independent samples t-test. Regression analyses tested for significant changes in concentration from the RCH center and possible correlations between soil parameters. Lastly, a simple relationship, adopted from Oguntunde et al., (2008) (Eq. 1), was used to compute the relative change of the soil properties.

(1)

$$RC (\%) = \frac{(PC - PA)}{PA} \times 100$$

RC is the relative change (increase or decrease), PC is the soil property measured on RCH sites, and PA is the soil property measured on AS.

RESULTS AND DISCUSSION

Hearth and Adjacent Site Comparisons

RCH samples were both chemically and morphologically different than AS samples. In the field, RCH soils displayed a distinct charcoal rich (Ac) layer. RCH Ac horizon were significantly thicker ($P < 0.01$) than those in the AS soils. Mean Ac thickness measured 9.5 ± 1.0 cm in RCH sites. In contrast, AS sites had a mean Ac thickness of only 2.6 ± 1.0 cm.

The high amount of charcoal may have impacted RCH bulk density values. Bulk density was significantly ($P < 0.01$) lower in RCH sites compared to AS. RCH values ranged from 0.3 to 1.0 g/cm³ while AS ranged from 0.6 to 1.0 g/cm³. Overall, the mean values for AS bulk density measured 12% higher than RCH soils. Similarly, in RCH soils in Ghana, Oguntunde et al., (2008) reported mean bulk density values were significantly ($P < 0.05$) lower by 9% compared to AS. This may be due to the physical effects of charcoal. Charcoal has been found to increase soil porosity, which is likely responsible for the decrease in RCH bulk density (Ayodele et al., 2009).

Charcoal production also impacted RCH soil organic carbon (SOC). RCH sites were 31% higher in SOC than AS soils (significant at $P < 0.01$) (Fig. 3). In a study of RCH sites in Ethiopia, Nigussie and Kissi (2011) found similar results, reporting a 5.1% increase in SOC at RCH sites compared to AS. Furthermore, previous biochar and black carbon research suggests increases in RCH SOC may be due to the aromatic structure of charcoal and its stability and persistence in the soil through time (Glaser et al., 2002, Liang et al., 2006). The recalcitrant aromatic structure of charcoal resists microbial degradation and remains relatively stable (Schneider 2012). This allows for the accumulation and retention of carbon-rich material in RCH soils (Hernandez-Soriano et al., 2015).

Major cation concentrations (Ca²⁺, $P < 0.01$; Mg²⁺, $P < 0.05$) were also significantly higher in RCH soils compared to AS (Fig. 3). In a study analyzing RCH sites in central Mexico, Gómez-Luna et al., (2009) similarly reported increased exchangeable cation concentrations in RCH sites. In Nigeria, Ogundele et al., (2011) reported significant increases in RCH

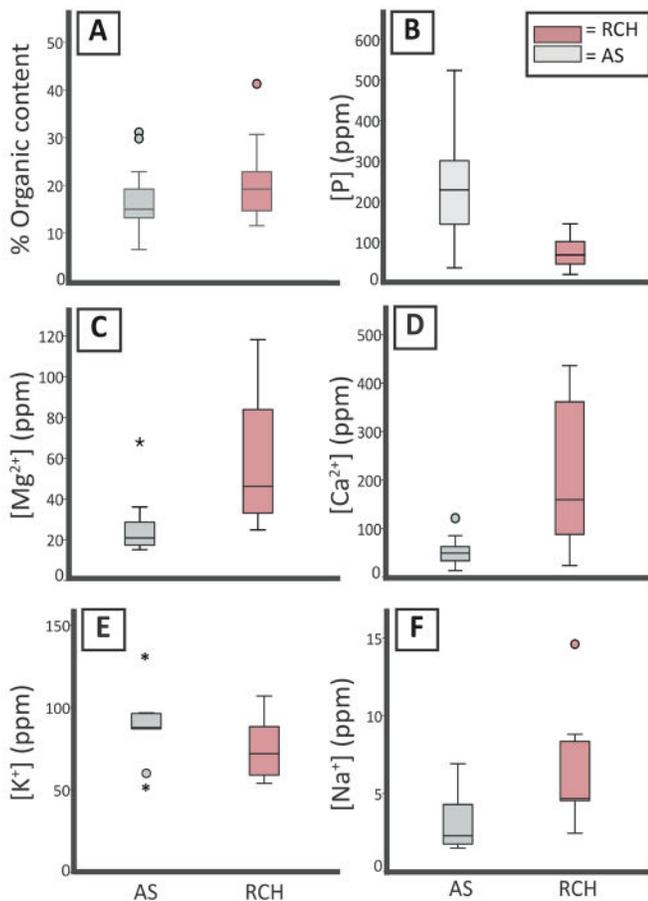


Figure 3. Box plots comparing all chemical data between RCH (red) and AS (grey) soils. Box plots show median values (solid horizontal line), 50th percentile values (box outline), 90th percentile values (whiskers), outlier values (circles), and extreme values (marked with a star). Outliers are any data points greater than 1.5X the interquartile range (IQR). IQR is defined as the difference between the upper quartile and the lower quartile (Q3-Q1). Extreme values represent data points greater than 3X the IQR. Plots A, B, and D had p -values < 0.01 . C and E had p -values < 0.05 , and F had a p -value > 0.05 .

cation concentrations as well. Cation concentrations may be linked to the abundance of charcoal in RCH soils. Fine pores within the charcoal particle “trap” and retain exchangeable bases. Additionally, carboxylic groups, which are produced along the core of the charcoal molecule through oxidation, increase the negative surface charge of charcoal and facilitate further exchangeable base retention (Glaser et al., 2002; Liang et al., 2006; Glaser et al., 2000).

In contrast, K^+ concentrations were significantly ($P < 0.05$) lower by 29% in RCH sites than AS (Fig. 3). Compared to previous studies (Nigussie

and Kissi 2011; Oguntunde et al., 2004) that reported comparable changes in all major cation concentrations, K^+ concentration patterns in the Connecticut RCH sites were anomalous. Such low potassium concentrations might be attributed to low levels of potassium in the vegetative feedstock used for production. Alternatively, changes to soil structure (e.g. coarser texture due to charcoal residue) may also have decreased exchangeable potassium concentrations within RCH sites (Ogundele et al., 2011).

Available phosphorus concentrations (AVP) were also significantly ($P < 0.01$) lower by 258% compared to AS (Fig. 3). At RCH sites in Pennsylvania, Young et al., (1996) also reported decreases in RCH AVP concentrations. Elevated cation concentrations may reduce soil phosphate concentrations through binding with phosphate ions forming insoluble compounds and causing phosphate to become unavailable and over time (Busman et al. 2002).

The Distance Effect: Lateral Trends at Hearth Sites

Soil chemistry associated with the RCH changed greatly over the first 5 to 10 m of the RCH boundary. Beyond that distance, surrounding soils displayed diminishing lateral changes in soil chemistry (Fig. 4).

Changes in Ac thickness followed this trend. RCH sites displayed mean thickness of 10.9 ± 1.0 cm at 0 cm from the RCH center. This value then decreased to 4.0 ± 1.0 cm at 10 m. Beyond 10 m, there was very little change, measuring 2.4 ± 1.0 cm at 20 m and 1.6 ± 1.0 cm at 30 m.

SOC content, major cations, and AVP concentrations also decreased laterally in a similar trend (Fig. 4). Mean SOC content dropped from $25 \pm 5\%$ at 0 m to $15 \pm 5\%$ at 10 m from the RCH center. SOC showed no significant change ($P > 0.05$) at 10, 20, and 30 m from the RCH center. Extractable mean Ca^{2+} concentrations were also highest at the RCH center (390 ± 1.0 ppm) and decreased with distance. Similarly, mean Mg^{2+} and Na^+ concentrations

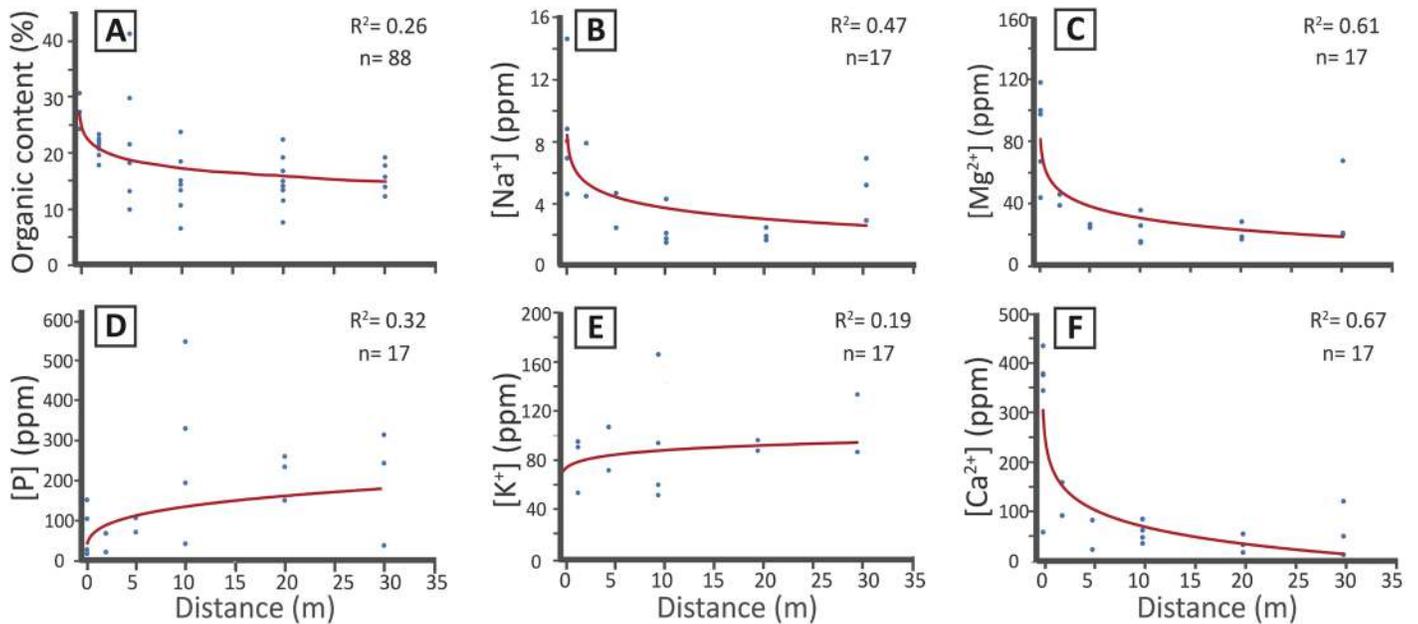


Figure 4. Scatter plots of chemical data from RCH site transects. Points represent a measurement taken from an individual soil sample. (A) Organic content determined from 88 select RCH site samples. (B)-(F): Chemical concentration determined from 17 RCH site locations. In every plot, all data points are shown, which demonstrates the variation in the data set.

measured 95 ± 1.0 ppm and 9.4 ± 1.0 ppm at the RCH center and then decreased to $23 \text{ ppm} \pm 1.0$ and 3 ± 1.0 ppm at 10 m. Beyond 10 m, Ca^{2+} , Mg^{2+} , and Na^{+} did not significantly ($P > 0.05$) change with increasing distance. Mean K^{+} and AVP concentrations displayed opposite trends, with values increasing within 10 m of the RCH and then remaining constant.

Changes to the Vertical Profiles: Comparing Hearth and Control Sites

Vertical soil profiles at RCH sites also differed from CS soils (Fig. 5). In RCH sites, the Ac layer reached a mean depth of 50 ± 10 cm. Many RCH profiles also displayed two Ac layers, which may indicate multiple episodes of charcoal production at the same site (Young et al., 1996). At RCH sites in Pennsylvania, Mikan and Abrams (1995) also found multiple charcoal layers at depth, extending from the O to the B horizons.

High SOC values extended considerably deeper in RCH sites as compared to CS sites (Fig. 5). At site SD10, SOC measured up to 4 times greater in RCH soils in the top 40 cm compared to CS. In the RCH profile, SOC peaked at 15 and 35 cm, which roughly

corresponded with the two Ac layers. In a study analyzing charred biomass in Terra Preta soils, Glaser et al., (2001) reported similar results, suggesting charcoal inputs not only affected the upper soil profile, but also influenced SOC at depth (Atkinson et al., 2010; Verheijen et al., 2010).

Charcoal production also affected RCH cation concentrations with depth (Fig. 5). Ca^{2+} , Mg^{2+} , and Na^{+} concentrations were consistently greater in RCH profiles compared to CS. At site SD10 Ca^{2+} reached a maximum concentration of 1060 ± 1.0 ppm at 30 cm depth. Mg^{2+} displayed 2 peaks (98 ± 1.0 ppm at 10 cm, 92 ± 1.0 ppm at 30 cm) that roughly corresponded to the Ac layers in the profile. At all depths, Na^{+} values were considerably higher in RCH, and K^{+} , meanwhile, displayed concentrations similar to CS concentrations at all depths.

The RCH did not have a considerable effect on soil P concentrations with depth. AVP concentrations were similar at depths > 20 cm, although from 0 to 20 cm, RCH AVP concentrations were significantly ($P > 0.01$) lower than CS (Fig. 5). This suggests AVP depletion only occurred in the surface of the soil profile.

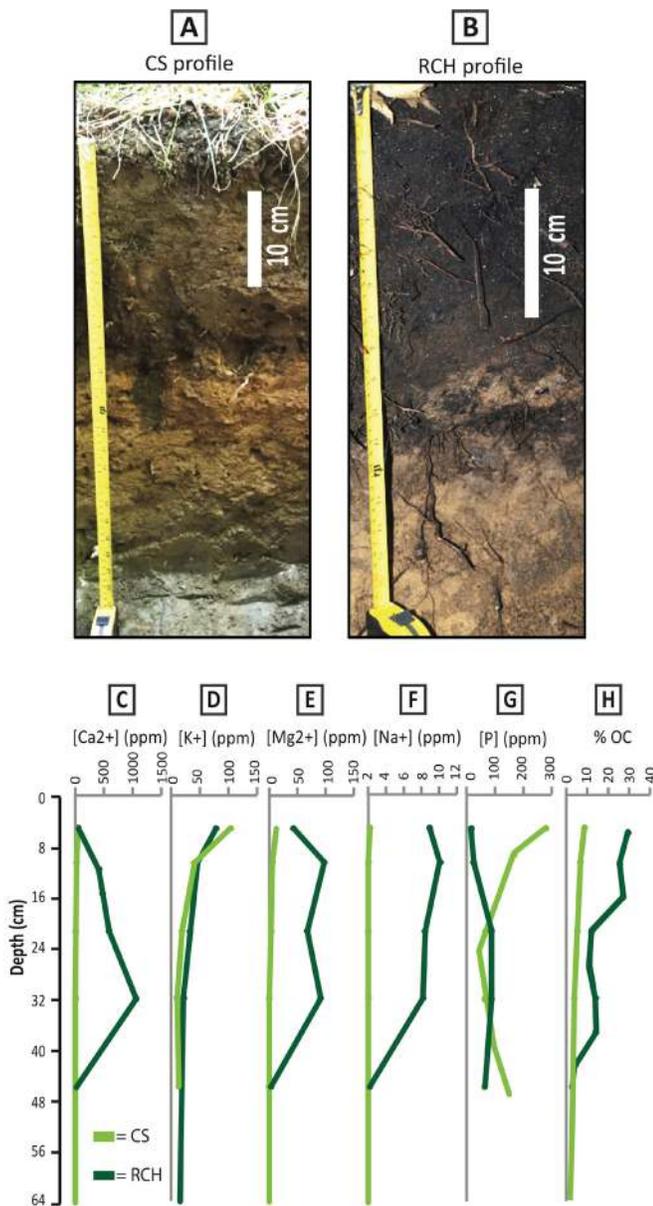


Figure 5. Chemical analyses of vertical soil profile in RCH and control site (CS). (A) Photograph of a CS vertical profile from the Mohawk State Forest. (B) Photograph of a RCH vertical profile from the Housatonic State Forest. (C)-(H): Combined chemical data from vertical profile samples that were collected in the CS (light green) and RCH (dark green).

CONCLUSIONS

Charcoal production introduced significant and lasting changes to the RCH soils of Litchfield County. RCH soils, as compared to AS, are enriched in most major cations and organic content, depleted in available phosphorus, and lower in bulk density. In the vertical profile, as compared to CS, RCH soils exhibit changes in most major cation concentrations and organic content at depths up to 40 cm. Changes in RCH soils also extend laterally, reaching distances of 5 to 10 m beyond the boundaries of the RCH. At distances greater than 10 m, the RCH soil effects diminish. Although this indicates the effects of charcoal production are site specific, these lateral trends are important to determining the effects of RCH sites on a landscape scale. Furthermore, as the changes within RCH soils have been found to affect nutrient availability and vegetative development, determining the extent of these changes is important to understanding the broader ecological impacts of charcoal production throughout Connecticut.

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