ELSEVIER

Small anthropogenic landforms from past charcoal production control moisture dynamics and chemistry in northcentral Appalachian soils

S. Bayuzick [a], D. Guarin [a], A. Bonhage [b], F. Hirsch [b], D.R. Diefenbach [a,c], M. McDill [a], T. Raab [b], P.J. Drohan [a,*]

[a] Department of Ecosystem Science and Management, Pennsylvania State University, University Park, PA 16802, United States
[b] Brandenburg University of Technology, Cottbus-Senftenberg, Cottbus, Germany
[c] U.S. Geological Survey, Pennsylvania Cooperative Fish and Wildlife Research Unit, Pennsylvania State University, University Park, PA 16802, United States

A B S T R A C T

Throughout the northeastern United States (U.S.) and Europe, relict charcoal hearths (RCHs) are regularly being discovered in proximity to furnaces once used for the extraction of metal from ore or quick-lime production; charcoal produced in hearths was used as a furnace fuel. Given previous research has shown that topographic and subsurface disturbance can be great when a hearth is constructed, we hypothesize that hearth construction alters surface hydrology and soil chemistry in environments in and near hearths. We used a landscape classification process to identify 6758 hearths near furnaces at Greenwood and Pine Grove Furnace State Park, central and southcentral Pennsylvania, U.S. Two types of digital elevation model wetness indexes were used to quantify surface hydrology effects in and around hearths. Modeled wetness conditions were compared to field soil volumetric water content in RCHs near Greenwood Furnace State Park. Modeled wetness indexes indicate that RCH interiors are significantly wetter than RCH rim areas; RCHs are acting as a landscape moisture sink. Results also indicate that RCHs on slopes result in downslope drier conditions below RCHs. Field measured volumetric water content indicates that as distance from the center of the hearth increases, soil moisture significantly decreases. Geomorphic position was found to not be related to RCH wetness. Soil from RCHs, compared to nearby native soils, has significantly higher total C, a lower Mehlich 3 extractable acidity, higher Ca and P. No trend was evident with RCH soil chemistry and geomorphic position. The high frequency of RCH occurrence, in proximity to the furnace's RCHs supported, suggests that RCHs today could locally be an important niche for understory flora and fauna. Further research could explore how RCHs might be affecting surrounding plant populations and how within RCH patterns, especially on hillslopes, might represent a distinctly different scale of physical and chemical variability.

1. Introduction

The production of charcoal, for use as fuel in furnaces, was a common past practice in the eastern U.S. (Rolando, 1992; Mikan and Abrams, 1995; Johnson et al., 2015; Potter and Brubaker, 2013; Raab et al., 2016, 2017; Hirsch et al., 2017; Bonhage et al., 2020a; Donovan et al., 2021) and Europe (Crutchley and Crow, 2010; Bond, 2007; Groenewoudt, 2007; Hardy et al., 2016, 2017; Hazell et al., 2017; Hirsch et al., 2017; Raab et al., 2015; Bonhage et al., 2020b; Schneider et al., 2020a). The peak period of U.S. charcoal production was between the mid-18th century and early 20th century (Gordon, 2000; Johnson et al., 2015; Straka, 2014; Straka, 2017; Hirsch et al., 2020), and in Europe from Medieval to Early Modern Times (10th to 19th century) (Hirsch et al., 2020).

Relict charcoal hearths (RCH) (Fig. 1) are semi-circular landscape features where charcoal was produced, which today can often be found across landscapes near furnaces, sometimes in regularly repeating

spacing intervals, and often in locally high densities. Research on North American RCHs is more recent than Europe's but has demonstrated that RCH construction was substantial with high concentrations found near furnaces (Potter and Brubaker, 2013; Marr and Wah, 2019; Bonhage et al., 2020a; Schneider et al., 2020a; Donovan et al., 2021; Schneider et al., 2022).

The potential legacy effect on ecosystems from charcoal production includes documented changes in some physical and chemical properties of soils (Mikan and Abrams, 1995; Donovan et al., 2021), effects on plant growth (Carrari et al., 2018; Criscuoli et al., 2014; Mikan and Abrams, 1995, 1996; Raab et al., 2017) or soil organisms (Garcia-Barreda et al., 2017; Gießelmann et al., 2019; Lasota et al., 2021), and cumulatively suggests that RCHs may represent unique ecological niches or states (e.g. Johanson and Brown, 2012).

Perhaps most disrupting to the local landscape is the physical construction of a hearth, which can change the site's surficial topography regardless of whether the hearth is built on a flat area or a slope. Hirsch

et al. (2020) developed a classification scheme that recognizes seven unique RCH morphologies that result from building hearths in different landscape positions (Hirsch et al., 2020); each has a unique surface and subsurface characteristic. For example, there are negative relief hearths created by placing wood within a 1 m deep by 2 m wide (depth and width can vary and be larger) pit instead of a platform; the pit shape varied from circular to rectangular (Groenewoudt, 2007; Hirsch et al., 2020). Negative relief hearths can be found across Europe and dating typically indicates an early Medieval period of construction. The flat landscape construction of an RCH often produces circular RCHs that are anywhere from 8 to 20 m in diameter but could be as large as 30 m in diameter (Hirsch et al., 2020). Like flat topography, these types of construction can reflect different aspects of a landscape including the type of wood used. On flat surfaces, there are three categorized types of hearth construction (all ~10–15 m diameter): 1) A charcoal mound (formed from continual reuse and incomplete charcoal excavation) that was either built on a flat stable landscape or on top of a raised pedestal (Hildebrandt et al., 2007; Hirsch et al., 2020); 2) A circular platform surrounded by a ditch or a series of pits dug around the platform (Raab et al., 2015, 2017; Schneider et al., 2018; Rutkiewicz et al., 2019; Hirsch et al., 2020); and 3) A circular platform surrounded by a raised rim (Hardy and Dufey, 2015; Hirsch et al., 2020; Swieder, 2019; Hirsch et al., 2020). There are also three construction types on sloped landscapes: 1) Angular RCHs created by using angular wood stacks creating a longitudinal shaped oval mound (Hennius, 2019; Hirsch et al., 2020; Klemm, 2005; Hirsch et al., 2020; von Berg, 1860; Hirsch et al., 2020); 2) An elliptical leveled platform created by moving upslope material downward and a downslope ditch (Ludemann and Nelle, 2002; Hirsch et al., 2020; Stolz and Grunert, 2010; Hirsch et al., 2020; Raab et al., 2017; Schneider et al., 2018; Hirsch et al., 2020); and 3) A leveled platform similar to 2 but with raised ridges from the removal of charcoal (Swieder, 2019; Hirsch et al., 2020; Tolksdorf et al., 2020; Hirsch et al., 2020; Hirsch et al., 2020).

The type of RCH construction is often indicative of landscape conditions that constrained construction techniques. For example, a pedestal was often used in areas where the soil was too unstable or wet for the wood piles (von Berg, 1860; Hirsch et al., 2020). Ditches, or series of pits, were hypothesized to act as a fire break to prevent forest fires (Friedrich II, 1779; Hirsch et al., 2020) or excavation of substrate to cover the wood mounds (Hirsch et al., 2020). Finally, a raised ridge was often indicative of shallow bedrock or from the removal of charcoal.

Hearth construction could thus change site soil water and biogeochemistry dynamics in comparison to non-hearth areas. The concave shape of RCH features, with rims surrounding, suggests that water could be captured within a hearth and thus produce a wetter condition than outside. A hearth built on a slope could in theory re-route surface or shallow subsurface flow around hearths and thus change area hydrology. Today, RCHs are noted to be enriched with pyrogenic carbon (Bonhage et al., 2020b) and numerous studies have found differences in soil carbon content of RCHs (Hirsch et al., 2018; Hardy et al., 2016, 2017; Kerré et al., 2016; Borchard et al., 2014; Bonhage et al., 2020b; Schneider et al., 2022). The physical, chemical, and geomorphic consequences of historical charcoal production (hearths, transportation networks, furnaces, etc.) and potential "legacy effect" on modern ecosystems is potentially substantial (Wohl, 2015; Raab et al., 2022).

Given the short time period of use relative to ecosystem development, hearth construction is thus an example of abrupt change in a forest ecosystem that has the potential to drive state changes and alter forest resilience (Sasaki et al., 2015; Suding and Gross, 2006; Ratajczak et al., 2018). For example, Straka (2014) notes an eastern US hearth could contain wood from an acre of forest (20–30 cords). Understanding how present-day abrupt forest change may drive shifts in forest composition, and the resilience of member entities, is becoming ever more important due to anthropogenic stresses (Scheffer, 2009; Petraitis, 2013; Ratajczak et al., 2018). Forest managers trying the adapt to anthropogenic stress can benefit from the study and quantification of past abrupt changes in
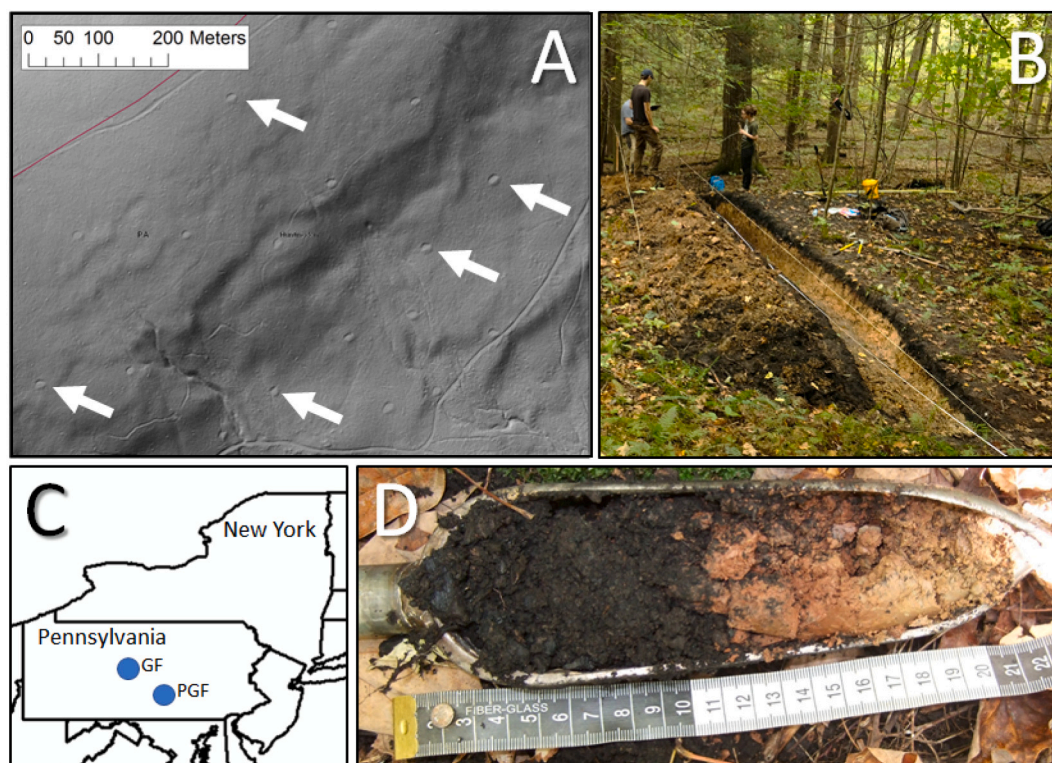

Fig. 1. A. Example density of hearths (noted by arrows) seen in 1 m resolution LiDAR data; B. Example hearth cross section showing rich surface layer of charcoal and soil organic carbon; C. The two northcentral Appalachian US study areas in this paper (GF = Greenwood Furnace; PGF = Pine Grove Furnace); D. Example enriched charcoal surface and subsurface Bw with rubification from high intensity charcoal burn (tape scale cm).

forests, especially when the legacy of past disturbance is still evident (Standish et al., 2014). We examined differences in RCH shape morphology metrics across a population of several thousand hearths, and in different geomorphic positions near two furnace operations in the northcentral Appalachians, U.S. To explore how RCHs influence surface hydrology, models of landscape wetness indices were developed from a geographic information system (GIS), within and outside of RCHs. We then chose a sub-population of these RCHs and measured field surface volumetric water content across hearths and outside of hearths and compared data to modeled wetness indices. To explore how surface soil chemical properties differ in RCHs compared to non-RCH areas we sampled surface soils and examined soil chemistry patterns.

2. Methods and materials

2.1. Study areas

Two furnace study areas (furnaces and surrounding hearths) were investigated in the U.S. state of Pennsylvania (Fig. 1) lying beyond the glacial limit (both iron production operations). Greenwood Furnace is found in Greenwood Furnace State Park, and the surrounding Rothrock State Forest, and Pine Grove Furnace is found within Pine Grove Furnace State Park, and the surrounding Michaux State Forest. The mean annual potential evapotranspiration at Greenwood Furnace is 650 mm (Waltman, 1997) and precipitation is 1016 mm (NOAA, 2022). The mean annual potential evapotranspiration at Pine Grove Furnace is 670 mm (Waltman, 1997) and precipitation is 1143 mm (NOAA, 2022). Mean soil temperature in the two study areas is 12 °C, mean moisture surplus is 350 to 450 mm and growing degree days 2600 to 3000 (Waltman, 1997). Greenwood Furnace was in operation from 1834 to the early 1900s (Pennsylvania Department of Conservation and Natural Resources, 2021a) and Pine Grove Furnace was in operation from about 1770 to 1895 (Pennsylvania Department of Conservation and Natural Resources, 2021b). Lithology common at the Greenwood Furnace study area consists of ridges of quartzite, quarzitic sandstone, and shale whereas valleys are comprised of less resistant sandstone, siltstone, shale and limestone (Hoskins, 1976). The Greenwood Furnace study area soils consist of Typic Hapludults (World Reference Base: Ferric Alisol), Typic Fragiudults (Fragic Alisol), Typic Fragiaquults (Fragic Alisol (Gleyic)), Aquic Fragiudults (Fragic Alisol), Aquic Fragiudalfs (Fragic Luvisol), Typic Dystrudepts (Dystric Cambisol), and Entic Haplorthods (Entic Podzol) (Soil Survey Staff et al., 2014b). Landform slopes, measured with a clinometer, range from 2 to 44 %. Lithology common at the Pine Grove Study area consists of ridges of quartzite, quartzose conglomerate with lower elevation hills and valleys of metarhyolite and valleys of dolomite (Berg, 1978). Common soils are Typic Hapludults, Typic Fragiaquults (Fragic Alisol (Gleyic)), Aquic Fragiudults (Fragic Alisol), Ultic Hapludalfs (Luvisol (Colluvic)), and Typic Dystrudepts (Dystric Cambisol) (Soil Survey Staff et al., 2014a; IUSS WRB, 2015). Landform slopes commonly range from 8 to 25 % with some ranging from 25 to 70 % (Soil Survey Staff et al., 2014a).

2.2. RCH mapping

Light Detection and Ranging (LiDAR) data for each study area were acquired from the Pennsylvania Spatial Data Access (PASDA) data repository. Data available for Greenwood Furnace State Park, and the surrounding Rothrock State Forest, were from 2006 to 2008 and of a ~ 1 m cell resolution (PAMAP Program et al., 2006). Data available for Pine Grove State Park and the surrounding Michaux State Forest were from the USGS QL2 2017 and of a ~ 1 m cell resolution (US Geological Survey, 2017a, 2017b, 2017c). ArcMap Desktop 10.6 was the primary software used for mapping and geospatial analysis (E.S.R.I, 2021b) Ground returns from the LiDAR data were converted into a vector data multipoint with elevation attributes (NAD83 UTM 18) using the ArcTool LAS to Multipoint (E.S.R.I, 2021a). The multipoint data were converted

into a 1 m cell resolution digital elevation model (DEM) using an Inverse Distance Weight (IDW) interpolation. Following the procedure from Fink and Drohan (2016), the DEM was produced using a processing filter power of 2.5 and a search radius of 50 m with a higher and lower limit of 15- and 10-m, respectively.

Study area DEMs were batch processed into hillslopes that increased in azimuth from 0 to 315 degrees at regular 45-degree intervals and for 30, 45, 60-degree altitudes. GRASS GIS (Grass Development Team, 2019) and the tool r.parma.scale (Wood, 1997) were used to create a slope gradient raster with a cell processing radius of 3 cells. A combination of both hillshades and slope gradient visualizations of each study area allowed for RCHs to be visually located and digitized. All RCHs were digitized at a 1:3000 scale per Raab et al. (2015) and Schneider et al. (2020a). This resulting data set was used to map the extent and number of RCHs with respect to each furnace area (Fig. 2). The density of RCHs (km^2) in each study area was determined in ArcMap using the point density tool with a 10 m cell size and 500 km^2 extent per cell (Fig. 2).

2.3. Hearth site morphology

To examine RCH shape morphology and soil wetness patterns, a 10 % subset of the RCH DEM mapping results were selected for each respective study area using the ArcMap Subset tool. The resulting datasets are henceforth known as the Greenwood subset and Pine Grove subset and include 84 and 374 RCHs, respectively. The Greenwood and Pine Grove subset sites were digitized into two sets of polygons. The first set consisted of polygons noted by the exterior boundary of the RCH polygon whereas the second set of polygons distinguishes the RCH rim from RCH interior areas (Fig. 3). Calculations that involve RCH polygons use the exterior RCH polygon unless otherwise stated. Mean DEM-derived landscape and hydrologic characteristics (e.g., elevation, slope, and topographic wetness) and RCH polygon shape characteristics (such as major and minor axis radius and center point) were collected using the Zonal Geometry ArcMap tool. The major axis was the longest axis of the polygon regardless of direction. The RCH major and minor axis was used to calculate RCH roundness:

$$Roundness = \frac{major\ axis}{minor\ axis}; where\ a\ roundness\ of\ 1\ is\ a\ circle$$

The roundness of RCHs was used to determine if RCH shape was related to landscape position. The original multipoint data set used to map RCHs was aggregated to a 3 m cells size DEM of the study areas. The GRASS GIS (GRASS Development Team, 2019) Geomorphon tool (based on a paper by Jasiewicz and Stepinski, 2013), with an annulus search radius of 375 cells and skip of 37 cells, was used to generate landforms. The Greenwood and Pine Grove subset data were coded to identify the landforms they were found in: 1. Summit, Ridges, and Spurs; 2. Backslopes; and 3. Hollows, Valleys, and Depressions.

2.4. Greenwood furnace field data collection and analysis

At the Greenwood study area 51 RCH sites were selected based on their distribution across a range of distances from the furnace operation and geomorphic positions. Each RCH was visited, and their major and minor axis was measured, along with landform's slope (via Suunto clinometer) that the RCH was on. To determine potential chemistry differences between native soils and RCH soils, soil samples were collected in summer months (non-rain conditions), in RCHs and adjacent control areas along a transect. Outside the RCH, 3 samples were taken at incremental distances of 10, 20, and 30 m. Samples were taken perpendicular to slope and remained within the RCH geomorphic position and with a 7.62 cm diameter by 7.62 cm long aluminum cylinder (volume = 347.57 cm^3). Soil Oa horizons were indistinguishable from A horizons and sampled together; no Oi or Oe horizons were sampled. At each site, soil from the top 5 cm was sampled (3 within the RCH and 3
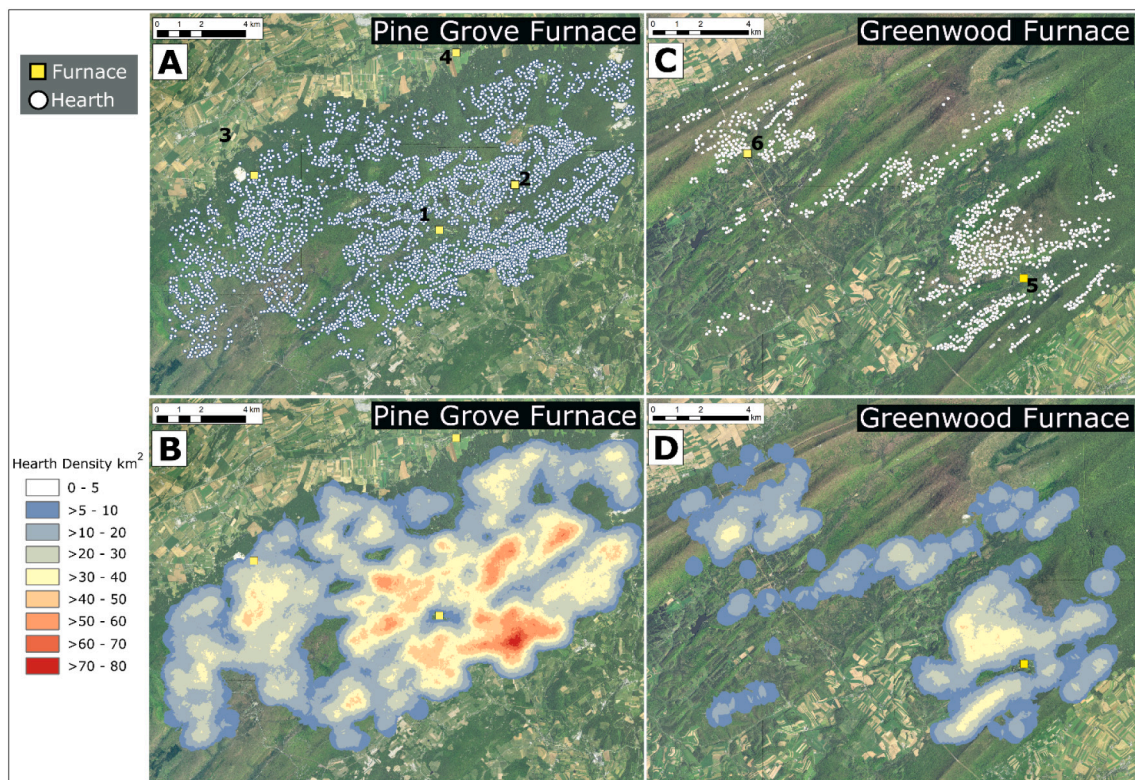
Fig. 2. Relict charcoal hearths mapped in this study, and their density, in Greenwood Furnace (A and B) and Pine Grove Furnace (C and D) study areas. Numbers indicate furnaces: 1 = Pine Grove; 2 = Mount Holly; 3 = Big Pond; 4 = Cumberland; 5 = Greenwood; 6 = Monroe.
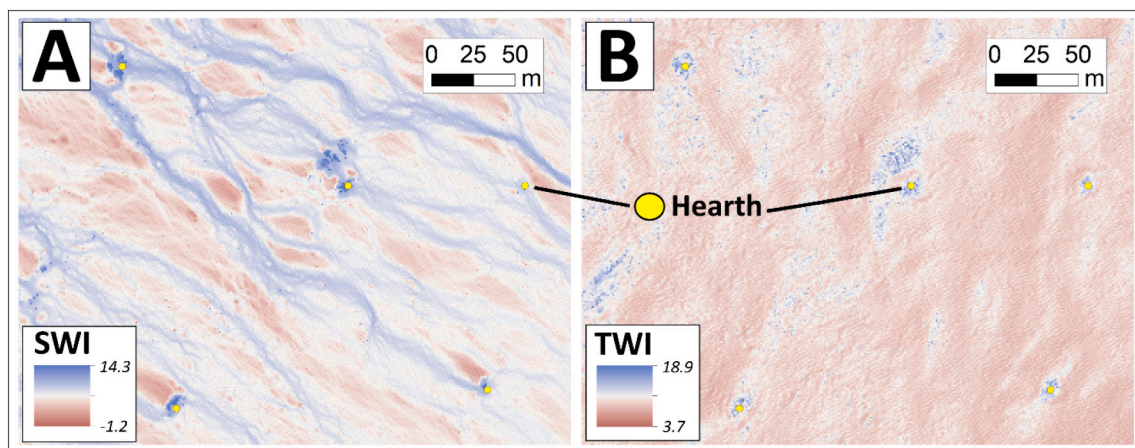

Fig. 3. Example wetness index models of the same area reflecting how hearth construction may influence immediate RCH location, and surrounding, hydrology. Yellow ovals are center points of hearths. *A. SAGA* software wetness index; and B. ArcMAP topographic wetness index. Upslope is to southeast and downslope to northwest.

outside the RCH). Within the RCH, samples were taken from: 1) RCH center; 2) halfway between the center and RCH rim; and 3) the RCH rim.

Alongside soil sampling areas, the mean of three volumetric water content (VWC) measurements (~5 cm tines) were taken with a Decagon 5TM capacitance probe. All plots were not sampled the same day, but measurements inside and outside of any one plot always occurred the same day; thus comparisons across plots represent a relative comparison across a range of antecedent moisture conditions. In addition, the 51 sites underwent the same DEM-derived roundness and hydrologic data analyses as previously explained.

Soil samples were sent to Agricultural Analytical Service Labs at The Pennsylvania State University. Soil pH was determined in water per

Eckert and Sims (2011). Soil cation exchange capacity (CEC) was determined by summation following Ross and Ketterings (2011). Total carbon and nitrogen were determined via dry combustion per Nelson and Sommers (1996) and Bremner (1996), respectively. Mehlich 3 weak acid extractions were measured by ICP-OES and used to determine extractable P, K, Ca, Mg, Fe, Al, S, Zn and Cu (Wolf and Beegle, 2011). EPA method 3050B + 6010 was used to determine the total recoverable metals and trace elements (U.S. EPA, 1996; U.S. EPA, 2014). Soil acidity was estimated using a modified Mehlich buffer (Hoskins and Erich, 2008; Wolf et al., 2008).

2.5. Surface hydrology analysis

To quantify potential landscape hydrologic differences from the construction of hearths, soil wetness was modeled in both study areas using two approaches. A 1-m DEM of each study area was analyzed using the software System for Automated Geoscientific Analysis (SAGA; Conrad et al., 2015). The 1-m DEM was processed first with the Fill Sinks tool (Wang and Liu, 2006; Conrad et al., 2015) to correct any elevation errors in the DEM. The filled DEM, flow width, and watershed basin parameters were inputted into the Flow Width and Specific Catch Area tool (Conrad et al., 2015), based on Gruber and Peckham (2008) and Quinn et al. (1991), to create the specific catchment areas of the study areas with multiple flow directions. The study area slope (in radians), and specific catchment areas, were used in SAGA's (Conrad et al., 2015) Topographic Wetness Index (TWI) tool (Beven and Kirkby, 1979; Moore et al., 1991; Böhner and Selige, 2006) to create a TWI of the study areas (Fig. 3). Likewise, SAGA's (Conrad et al., 2015) Wetness Index (SWI) tool (Böhner et al., 2002; Böhner and Selige, 2006), and a filled 1-m DEM, was used to create a SWI raster for each study area. The SWI is like a TWI but it's algorithm does not model flow as a narrow path, thus cells in low landscape positions, and a short vertical distance to a channel, will have a higher potential soil moisture versus the TWI calculation (Mattivi et al., 2019).

Mean TWI and SWI index values for the Greenwood and Pine Grove subset data were extracted using the digitized RCH polygons (RCH rim and interior RCH areas). The RCH polygon represents the hearth. To derive a non-hearth TWI or SWI value, a 60 m buffer around the center of all subset data RCHs was created. The value of 60 m was chosen because this is roughly $3\times$ the mean major axis diameter from in field measurements of the 51 RCHs at Greenwood Furnace. An idealized RCH ellipse was created using the mean major and minor axis from in field data analysis along with the centroid azimuth from the Zonal Geometry tool. This ellipse was then removed from the 60 m buffer that was generated to create the non-RCH hydrologic area. Within each non-RCH hydrologic area, 50 points were randomly generated 1 m apart locally (within the same hydrologic area polygon) and 0.5 m apart globally (if two hydrologic area polygons were close or overlapping). The ellipse removal insured that the generated points would not fall within an existing RCH. Data values at each of the 50 points in each non-RCH hydrologic area were extracted from the SWI and TWI rasters to generate mean TWI and SWI values for non-RCH control areas. The mean TWI and SWI for control areas represents the on-RCH hydrologic area. The mean TWI and SWI values of the RCH rim and RCH interior polygons were also calculated for comparison.

2.6. Statistical analysis

A one-way analysis of variance (ANOVA) was used to determine the significant differences between roundness of RCH and landscape position, and VWC and sampling position. Paired *t*-tests were used to compare RCH (interior) TWI and SWI values and the surrounding hydrologic areas (exterior) and between RCH rim and RCH interior chemistry and VWC (rim removed from interior measurements). A Two Sample *t*-test was used to compare morphology of RCHs between the Greenwood subset dataset and the Pine Grove subset dataset. Each test was performed at an alpha of 0.05 in Minitab Version 19 (Minitab 19 Statistical Software, 2020).

3. Results

3.1. RCH morphology, landscape position, and wetness

A total of 1234 RCHs were identified in the Greenwood Furnace study area (Fig. 2) spanning an area of 105 km^2 (average study-wide density of 11.8 km^2) whereas in the Pine Grove Furnace study area 4140 RCHs (Fig. 2) were mapped spanning an area of 158 km^2 (average

density of 26.2 km^2). This results in a hearth density of 5 to 40 per km^2 in the vicinity of Greenwood Furnace (Fig. 2) and 5 to 80 per km^2 at Pine Grove Furnace (Fig. 2). Both study sites have local areas of high RCH density that surround different iron furnaces. For example, within 3–4 km of the Greenwood Furnace the density of RCH features increases to over 30 RCH per km^2; similar densities occur near Monroe Furnace to the north. Within 3–4 km of Pine Grove Furnace RCH density can be over 70 per km^2 and near Mount Holly Furnace densities can be over 60 per km^2 (Fig. 2).

The Greenwood subset RCH, Greenwood Field Study, and Pine Grove subset RCH hearth morphology metrics (mean major and minor axis and roundness coefficient) for the entire RCH and the interior RCH are presented in Table 1. A 2-sample *t*-test comparing the morphology metrics of the Greenwood subset and the Pine Grove subset is presented in Table 2. Greenwood subset RCHs have a significantly larger major RCH axis than the Pine Grove RCHs for both the full RCH and the interior of the RCHs. Greenwood subset RCHs are also significantly rounder (both full RCH and interior RCHs).

The landscape position and ANOVA Tukey comparisons of morphology data by geomorphic group are presented in Table 3. There was no significant difference in RCH major axis, minor axis, or roundness difference by geomorphic groups for the Greenwood Furnace subset and the Greenwood Furnace field study. Pine Grove subset RCH polygons in the backslope geomorphic position had a major axis that was significantly smaller than hollows, valleys and depressions. Pine Grove subset RCH polygons in summits, ridges and spurs had a significantly smaller minor axis than hollows, valleys, and depressions. No difference in roundness was found between any geomorphic position in the Pine Grove subset dataset.

The control, non-hearth polygon exterior area data for the Greenwood Furnace subset, Greenwood Furnace Field, and Pine Grove subset RCH hearth morphology metrics (mean major and minor axis and roundness coefficient), landscape position, and ANOVA Tukey comparisons of morphology data by geomorphic group are presented in Table 4. At Greenwood Furnace, in the subset and field data sets, no significant difference was found between RCH size, roundness, slope and wetness. The Pine Grove Furnace subset data had significantly drier TWI values on backslopes and wetter SWI values in hollows, valleys and depressions versus other geomorphic groups. Elevation in the Pine Grove Furnace subset data was significantly different between geomorphic groups with summits, ridges, and spurs highest and hollows, valleys and depressions lowest.

3.2. RCH hydrology analysis

An example SAGA SWI and ArcMap TWI wetness model for a landscape with high-relief (steeper) and low-relief RCHs is displayed in Fig. 3. The SWI model shows that RCHs potentially can have a lasting effect on landscape hydrology by: (1) routing water around RCHs; (2) creating a wetter interior, but (3) on the downslope side of RCHs creating a drier position. Low-relief RCH positions have a uniformly wetter interior compared to high-relief RCHs and outside control areas.

Results of digitized hearth wetness (TWI and SWI) paired *t*-tests between the rim and interior areas of polygons for the Greenwood subset data, Greenwood field data, and Pine Grove subset data are presented in Table 5. All three data sets had significantly higher TWI or SWI values in interiors versus rims.

Paired t-test results comparing digitized hearths (interior) to exterior, non-hearth polygon controls (exterior) for wetness (TWI, SWI), elevation, slope and field-collected VWC (for Greenwood Field Study only due to COVID travel restrictions) are presented in Table 6. Digitized hearth areas in the Greenwood subset and field data sets had significantly higher TWI and SWI values versus exterior areas; slope was significantly lower in hearth interiors too. The Greenwood Field data set had a significantly higher VWC versus exterior hearth areas. Digitized hearth areas in the Pine Grove subset dataset had significantly higher

Table 1

Mean hearth morphology, wetness, elevation, and slope: A. Greenwood subset RCH polygons; B: Greenwood field study RCH polygons; C: Pine Grove Subset Data Set RCH polygons.

	n	Major Axis (m)	Minor Axis (m)	Roundness (m/m)	TWI	SWI	Elevation (m)	Slope (°)
A.								
All Hearths	84	20.3 (2.6)[a]	16.4 (2.2)	1.2 (0.2)	9.5 (0.6)	3.5 (0.6)	420.4 (92.4)	22.7 (5.6)
Interior Hearth Area	84	14.9 (2.4)	9.3 (1.8)	1.6 (0.3)				
B.								
All Hearths	51	19.7 (2.0)[a]	17.1 (1.9)	1.2 (0.1)	9.5 (0.4)	3.4 (0.6)	408.6 (88.7)	22.8 (5.8)
Interior Hearth area	51	14.1 (2.1)	9.2 (1.5)	1.6 (0.3)				
C.								
All Hearths	374	18.2 (1.8)[a]	16.0 (1.7)	1.1 (0.1)	13.1 (0.5)	5.0 (0.7)	379.5 (85.0)	8.1 (3.1)
Interior Hearth area	374	13.3 (1.7)	9.6 (1.7)	1.4 (0.3)				

[a] Mean (standard deviation).

Table 2

Two sample t-test results of hearth morphology values between Greenwood subset dataset RCH polygons and Pine Grove Subset dataset RCH Polygons A. RCH polygons; B: Interior RCH polygons only.

Attribute	Greenwood RCHs $n = 84$	Pine Grove RCHs n = 374	*p*-value
A.			
Major Axis	20.3 (2.6)[a]	18.2 (1.8)	<0.001
Minor Axis	16.4 (2.2)	16.0 (1.7)	0.086
Roundness	1.2 (0.2)	1.1 (0.1)	<0.001
B.			
Major Axis	14.9 (2.4)[a]	13.3 (1.7)	<0.001
Minor Axis	9.3 (1.8)	9.6 (1.7)	0.279
Roundness	1.6 (0.3)	1.4 (0.3)	<0.001

[a] Mean (standard deviation).

TWI and SWI values versus exterior areas, elevation was significantly higher in exterior areas and slope was significantly lower in hearth interiors.

Table 7 presents ANOVA Tukey comparison results of VWC differences in the Greenwood field data set by hearth position. Hearth centers have significantly higher VWC values compared to rims and outside. No difference is found between hearth centers and the halfway point within hearths between the center and rim.

3.3. RCH chemistry

Chemistry data (element concentrations) from the Greenwood field data set is presented in Table 8. Greenwood field study RCHs have significantly higher total C compared to exterior areas. Mean Mehlich 3 extractable Ca, Al, Fe, and CEC in RCH soils is significantly higher compared to exterior areas. Mehlich 3 P and S are significantly lower in RCH soils. Soil acidity is significantly higher in RCH soils compared to exterior areas.

ANOVA Tukey comparisons of RCH mean soil chemistry by sampling position within a hearth to exterior areas is presented in Table 9. Hearths have significantly lower S in rims and center positions in comparison to halfway positions between the center and rim and exterior areas outside of hearths. Mehlich 3 extractable Al is significantly higher in the hearth center and halfway point versus the rim and exterior area. Mehlich 3 extractable Fe is significantly higher in the center and halfway point versus the rim and exterior areas. Acidity is significantly higher in interior RCH areas when compared to exterior areas.

4. Discussion

4.1. RCH extent and geomorphology

While the occurrence of RCHs in the vicinity of Greenwood Furnace has been known for decades, their number or extent has not been documented. Results from this study suggest there are over 1200 RCHs in the Greenwood Furnace area and over 4100 RCHs were found in the

vicinity of Pine Grove Furnace; RCH densities at Pine Grove Furnace are often twice the density at Greenwood Furnace. Prior mapping across the area of South Mountain, where Pine Grove and other furnaces are, uncovered over 3000 RCHs in a 40 km long area between South Mountain's northeast end and Caledonia Gap (Potter and Brubaker, 2013).

Differences in RCH shape were found between the Greenwood and Pine Grove Furnace study areas, which we hypothesize is due to inherent landscape geomorphic differences. The difference between the major axis in the Greenwood subset RCH and the Pine Grove subset RCH can mostly be attributed to the site stability and lower slopes of Greenwood allowing for larger RCHs to be able to be created; similar results were found by Bonhage in Connecticut, USA (Bonhage et al., 2020a). The larger roundness ratio in Greenwood subset RCHs when compared to the Pine Grove subset, RCHs indicates less circular RCHs which can be attributed to the larger major axis of RCHs. There was also no difference in exterior RCH size or roundness by geomorphic position. The geometric shape of RCHs does not differ by geomorphic position. Compared to other U.S. studies, hearths at Pine Grove Furnace and Greenwood Furnace have a larger diameter than those studied by: Raab et al. (2017) in Connecticut, U.S. (diameter 10 m); Mikan and Abrams (1995) at Hopewell Furnace, eastern Pennsylvania (mean 12.2 m charcoal area); and Marr and Wah (2019) at Caledonia Furnace in southcentral, Pennsylvania (~11 m), which may suggest that colliers, professional charcoal makers, found an efficient method for creating RCH platforms regardless of landscape position and that a circular-oval shape was the most effective shape to hold the wood to burn. Greenwood Furnace RCHs were similar in major and minor axis extent for each geomorphic position, but at Pine Grove Furnace RCHs were ~ 0.5 m larger (major and minor axis) in lower landscape positions.

The generally similar size of RCHs may imply that similar amounts of timber for charcoal creation were used in in all geomorphic groups, or that log length was similar, or this RCH size was simply the largest practical size for the human crews in these areas given the slope stability constraints. The results from Pine Grove Furnace, where larger RCHs occurred in lower geomorphic positions, may suggest a relationship with lower landscape positions being more stable landforms or may reflect the ease of creation in lower geomorphic areas compared to less stable landscape positions such as backslopes.

4.2. RCH hydrology analysis

Results from this study highlight the unique hydrologic characteristics of RCHs over a short spatial extent. Results also point to a broader ecosystem effect given that the construction of RCHs was shown to be affecting the overall landscape surface hydrology. TWI and SWI ANOVA results of RCHs across geomorphic positions suggests that no matter what landscape position (see Fig. 3 to see TWI values in high relief vs low relief landscape positions), RCH interiors are wetter. This trend indicates the stability in RCH construction despite erosional forces on differences in slopes.

We infer from the shapes of RCHs found in this study that RCHs

Table 3

Tukey ANOVA comparisons of mean hearth morphology, wetness, elevation and slope: A. Greenwood subset RCH polygons; B: Greenwood field study RCH polygons; C: Pine Grove subset RCH polygons.

	n	Major Axis (m)	Minor Axis (m)	Roundness (m/m)	TWI	SWI	Elevation (m)	Slope (°)
A.								
Hearths by Geomorphic Groups								
Summits, Ridges and Spurs	28	20.5 (2.2) a	16.7 (1.7) a	1.2 (0.2) a	9.4 (0.4) a	3.5 (0.7) a	459.6 (84.5) a[‡]	22.0 (6.8) a
Backslopes	39	20.3 (2.5) a	16.4 (2.1) a	1.3 (0.2) a	9.7 (0.7) a	3.4 (0.6) a	410.1 (94.8) ab	23.0 (4.7) a
Hollows, Valleys and Depressions	17	19.8 (3.6) a	16.1 (2.9) a	1.2 (0.2) a	9.5 (0.6) a	3.5 (0.6) a	379.6 (78.7) b	23.0 (5.8) a
B.								
Hearths by Geomorphic Groups								
Summits, Ridges and Spurs	17	20.0 (1.5)[†] a	17.0 (1.8) a	1.2 (0.1) a	9.4 (0.3) a	3.4 (0.6) a	459.5 (102.2) a	21.2 (4.8) a
Backslopes	10	19.6 (1.6) a	17.7 (1.8) a	1.1 (0.1) a	9.5 (0.2) a	3.3 (0.6) a	403.9 (52.2) ab	25.0 (7.1) a
Hollows, Valleys and Depressions	24	19.4 (2.4) a	16.9 (2.0) a	1.2 (0.1) a	9.5 (0.4) a	3.5 (0.6) a	374.5 (75.3) b	22.9 (5.7) a
C.								
Hearths by Geomorphic Group								
Summits, Ridges and Spurs	107	18.2 (1.9) ab	15.8 (1.7) a	1.2 (0.1) a	13.2 (0.5) a	4.9 (0.6) a	412.0 (81.9) a	7.6 (2.9) a
Backslopes	127	17.9 (1.8) a	15.8 (1.8) ab	1.1 (0.1) a	12.9 (0.5) a	4.8 (0.7) a	385.1 (82.7) a	9.0 (3.3) a
Hollows, Valleys, and Depressions	140	18.5 (1.6) b	16.3 (1.5) b	1.1 (0.1) a	13.2 (0.5) a	5.3 (0.8) a	349.6 (79.6) a	7.7 (3.0) a

[†] Mean (standard deviation).

[‡] Within a sub-table (A, B, or C) different letters between rows in a column indicate significant differences at an alpha = 0.05.

influence wetness primarily because of (a) their morphology in relation to local relief and (b) substrate properties; geomorphic group had no effect on wetness. Steep RCH rims can quickly shed water into the RCH interior where it infiltrates; percolation may be limited by subsurface horizons with dissimilar particle sizes, or higher carbon contents, that result in higher water capacities and/or water slowing at boundaries with buried native soils. The higher water holding capacity in RCHs (compared to exterior areas) has been noted where higher total carbon contents in RCHs are found (Hirsch et al., 2018; Hardy et al., 2016, 2017; Kerré et al., 2016; Borchard et al., 2014; Bonhage et al., 2020b; Schneider et al., 2020b). Results from our study also show that RCH VWC is variable across a lateral gradient of the RCH, and to the area

outside the RCH, with soils becoming dryer towards the RCH rim. This difference in VWC between the center of the RCH, the rim, and exterior area further indicate the effects of RCH surface morphology in area hydrology. Previous research has noted that the soil water content of RCHs can be higher than surrounding reference soils but also variable across a singular RCH site or between multiple RCH sites (Schneider et al., 2020b). Hearths in sandy soils of Germany have also been shown to drain quickly (Schneider et al., 2020b).

4.3. RCH chemistry comparison

Hearths at Greenwood Furnace are found to have higher total carbon

Table 4

Control, non-hearth polygon exterior area, Tukey ANOVA comparisons of RCH outer (non-hearth) wetness, elevation and slope. A. Greenwood subset; B: Greenwood field study; 7C: Pine Grove subset.

	n	Polygon TWI	Polygon SWI	Elevation (m)	Slope (°)
A.					
All Control areas	84	9.1 (0.6)[†]	3.2 (0.4)	420.6 (91.9)	28.1 (7.7)
Control areas by Geomorphic Groups					
Summits, Ridges, and Spurs	28	9.0 (0.4) a	3.3 (0.3) a	459.0 (84.3) a[‡]	27.2 (8.9) a
Backslopes	39	9.3 (0.7) a	3.2 (0.4) a	410.2 (94.6) ab	28.3 (6.0) a
Hollows, Valleys and Depressions	17	9.0 (0.7) a	3.2 (0.5) a	381.3 (77.8) b	29.0 (9.4) a
B.					
All Control areas	51	9.1 (0.4)	3.2 (0.5)	408.7 (88.2)	27.5 (7.5)
Control areas by Geomorphic Groups					
Summits, Ridges, and Spurs	17	9.0 (0.3) a	3.2 (0.5) a	458.4 (102.4) a	25.9 (6.4) a
Backslopes	10	9.2 (0.3) a	3.2 (0.3) a	403.5 (52.5) ab	29.2 (8.8) a
Hollows, Valleys and Depressions	24	9.1 (0.5) a	3.3 (0.5) a	375.7 (74.5) b	27.9 (7.7) a
C.					
All Control areas	374	12.7 (0.6)	4.6 (0.6)	379.7 (84.9)	9.9 (4.1)
Control areas by Geomorphic Groups					
Summits, Ridges, and Spurs	107	12.8 (0.6) a	4.5 (0.7) a	411.6 (81.8) a	9.5 (4.2) a
Backslopes	127	12.5 (0.6) b	4.4 (0.5) a	385.3 (82.7) b	11.1 (4.1) b
Hollows, Valleys, and Depressions	140	12.9 (0.6) a	4.8 (0.7) b	350.4 (79.7) c	9.2 (4.2) a

[†] Mean (standard deviation).

[‡] Within a sub-table (A, B, or C) different letters between rows in a column for each Control areas by Geomorphic Groups indicate significant differences at an alpha = 0.05.

Table 5

Paired t-test results of SWI or TWI values between RCH rim and interior polygons (Interior-Rim). A. Greenwood subset dataset n = 84; B: Greenwood field study dataset $n = 51$; C: Pine Grove subset dataset $n = 374$.

Attribute	RCH Polygon Rim	RCH Polygon Interior	p-value
A.			
TWI	9.0 (0.6)[a]	10.4 (0.6)	<0.001
SWI	3.2 (0.6)	3.9 (0.7)	<0.001
B.			
TWI	8.9 (0.3)	10.4 (0.4)	<0.001
SWI	3.1 (0.6)	3.9 (0.7)	<0.001
C.			
TWI	12.5 (0.5)	13.9 (0.5)	<0.001
SWI	4.6 (0.7)	5.5 (0.8)	<0.001

[a] Mean (standard deviation).

Table 6

Paired t-test results of RCH areas and exterior controls areas for wetness, elevation, slope, and volumetric water content when applicable (Interior-Exterior). A. Greenwood subset dataset n = 84; B: Greenwood field study dataset n = 51; C: Pine Grove subset dataset $n = 374$.

Attribute	Interior	Exterior	p-value
A.			
TWI	9.5 (0.6)[a]	9.1 (0.6)	<0.001
SWI	3.5 (0.6)	3.2 (0.6)	<0.001
Elevation (m)	420.4 (92.4)	420.6 (91.9)	0.282
Slope (°)	22.7 (5.7)	28.1 (7.7)	<0.001
B.			
TWI	9.5 (0.4)	9.1 (0.4)	<0.001
SWI	3.4 (0.6)	3.2 (0.5)	0.002
Elevation (m)	408.6 (88.7)	408.7 (88.2)	0.752
Slope (°)	22.8 (5.8)	27.5 (7.5)	<0.001
Volumetric Water Content (v/v)	22.6 (4.0)	20.7 (4.3)	0.001
C.			
TWI	13.1 (0.5)	12.7 (0.6)	<0.001
SWI	5.0 (0.7)	4.6 (0.6)	<0.001
Elevation (m)	379.5 (85.0)	379.7 (84.9)	0.002
Slope (°)	8.1 (3.1)	9.9 (4.1)	<0.001

[a] Mean (standard deviation).

concentrations than their reference forest soils and this may be attributed to pyrogenic carbon or soil organic matter. Donovan et al. (2021) found RCH soils have a significant increase in soil organic matter content when compared to surrounding native soils. Hirsch et al. (2017) attributed an increase in carbon to charcoal amended RCH soils (Hirsch et al., 2017), but non-pyrogenic SOM also is common (Borchard et al., 2014, Kerré et al., 2016, 2017; Bonhage et al., 2020b).

RCH soils have higher soil acidity than surrounding soils, however, this cannot be attributed to hydrogen ions as there is no difference in pH between RCH and native soils. We thus infer that increase in acidity in RCH soils results from an increase of bound Al ions on CEC sites (the Mehlich 3 extractable Al in RCH soils of this study is higher than surrounding soils), which is plausible given the low soil pH. Aluminum in RCH soils could, if high enough, limit some vegetation production by limiting root growth and inhibiting nutrient uptake (Cronan et al., 1989; Decker and Boerner, 1997; Burnham et al., 2017).

Table 7

Tukey ANOVA comparisons of volumetric water content by sample position in the Greenwood Field study dataset.

	n	VWC (%/%)
RCH Sample Position		
Center	51	24.0 (6.3)[†]a[‡]
Halfway	51	22.3 (4.0) ab
Rim	51	20.7 (4.3) b
Outside	51	21.5 (4.3) b

[†] Mean (standard deviation).

[‡] Letters in a row that are different indicate a significant difference at alpha = 0.05.

Table 8

Field Study Dataset - Paired t-Test (interior-exterior) results of mean soil chemistry within RCH (interior) and the surrounding area (exterior). $n = 51$.

Parameter	Units	Interior	Exterior	p-value
pH		4.3 (0.5)[a]	4.2 (0.4)	0.483
P	mg kg^{-1}	13.9 (4.3)	17.7 (7.9)	<0.001
K	mg kg^{-1}	82.1 (24.4)	90.3 (28.0)	0.068
Mg	mg kg^{-1}	49.7 (56.5)	43.6 (40.8)	0.263
Ca	mg kg^{-1}	333.0 (395.0)	203.0 (173.0)	0.011
Zn	mg kg^{-1}	7.7 (22.8)	3.45 (2.05)	0.189
Cu	mg kg^{-1}	1.8 (0.8)	2.0 (1.0)	0.191
S	mg kg^{-1}	12.3 (2.6)	13.8 (3.3)	0.005
Acidity	cmol+ kg^{-1}	19.9 (4.1)	15.4 (3.6)	<0.001[‡]
CEC	cmol+ kg^{-1}	16.6 (1.6)	15.0 (1.5)	<0.001
Extractable Al	mg kg^{-1}	917.0 (279)	540.0 (349.0)	<0.001[‡]
Extractable Fe	mg kg^{-1}	236.5 (63.7)	164.0 (83.4)	<0.001[‡]
Total carbon	%	20.0 (7.0)	14.3 (11.5)	<0.001
Total nitrogen	%	0.5 (0.2)	0.6 (0.4)	0.235

[a] Means (standard deviation).

Macronutrients in RCHs have been found to be lower in RCH soils when compared to surrounding native soils. For example, Donovan et al. (2021), found significantly lower K, and P in RCH soils compared to surrounding native soils and lower total nitrogen (but this was not significant). Greenwood Furnace RCHs had lower mean soil P but not K. Lower available P could limit plant growth on RCHs compared to the surrounding area. Results from Greenwood Furnace RCHs show that only Ca was higher in RCH versus native soils. Lastly, Greenwood Furnace RCHs had lower S concentrations in RCH soils. Several soil chemical parameters exhibited high variability and no statistical differences. Such variability suggests we may need a larger sample size to detect potential differences, RCHs were only used once, substantial local variability in the properties we measured, or that the RCH creation process results in highly variable conditions within hearths.

5. Conclusion

The legacy of RCH creation results in soil moisture and chemical patterns within RCHs that are unique to where RCHs occur emphasizing the significance of these small-scale landforms for site conditions and especially soil chemistry. Moreover, our results prove that relatively small, punctiform anthropogenic relief modifications from historical charcoal production can noticeably affect soil wetness on slopes and thus the legacy effect of RCHs goes far beyond their actual spatial dimension. Results indicate that this legacy effect is declining with distance to former processing facilities as the density of RCHs at both study areas was typically greatest closest to furnaces. Regarding the most notable specific effects we can draw the following conclusions.

Table 9
Field Study Dataset –ANOVA Tukey comparisons of mean soil chemistry across RCH sampling positions. n = 51.

Parameter	Units	RCH Center	Halfway	RCH Rim	Outside RCH
pH		4.3 (0.6)[†] a	4.3 (0.5) a	4.2 (0.5) a	4.2 (0.4) a
P	mg kg^{-1}	14.1 (5.1) a[‡]	13.5 (4.4) a	14.2 (6.1) a	17.7 (7.9) b
K	mg kg^{-1}	76.4 (28.2) a	81.9 (28.2) a	87.8 (33.5) a	90.3 (28.0) a
Mg	mg kg^{-1}	46.2 (46.1) a	51.0 (66.5) a	52.0 (63.6) a	43.6 (40.8)a
Ca	mg kg^{-1}	295.5 (422.9)a	355.2 (540.1) a	348.8 (417.2) a	202.9 (173.2) a
Zn	mg kg^{-1}	14.0 (67.3) a	4.6 (2.6) a	4.6 (2.9) a	3.5 (2.1) a
Cu	mg kg^{-1}	1.7 (1.0) a	1.7 (1.3) a	1.9 (1.3) a	2.0 (1.0) a
S	mg kg^{-1}	13.5 (3.8) a	12.3 (3.5) ab	11.1 (3.0) b	13.8 (3.3) a
Acidity	cmol+ kg^{-1}	19.4 (5.6) a	19.8 (4.1) a	20.3 (5.7) a	15.4 (3.6) b
Extractable Al	mg kg^{-1}	1057.5 (325.5) a	998.4 (349.2) a	696.3 (408.3) b	539.9 (348.6) b
Extractable Fe	mg kg^{-1}	261.2 (90.0) a	244.4 (80.9) ab	203.8 (96.4) bc	164.0 (83.4) c
Total carbon	%	17.1 (8.0) a	18.0 (5.2) a	24.9 (14.0) b	14.3 (11.5) a
Total nitrogen	%	0.4 (0.2) a	0.5 (0.2) ab	0.6 (0.4) b	0.6 (0.4) ab

[†] Mean (standard deviation).
[‡] Letters in a row that are different indicate a significant difference at alpha = 0.05.

- Low SWI and TWI rim values, coupled with high TWI and SWI values within RCH interiors, suggest that RCHs have a specific landscape hydrological footprint and can act as soil moisture sinks.
- Field VWC data support patterns seen in wetness index modeling results.
- Modeling SWI and TWI, in and around RCHs, shows that RCHs could deflect surface water movement.
- Soil chemistry results show that the chemical footprint of RCHs differs from that of non-RCH areas with increased concentrations of some base cations, such as Ca, and the loss of macronutrients such as P and K.
- Soil chemistry results also indicate higher RCH acidity, which is most likely due to the increase in soil Al; higher Al could limit some root growth and soil biota.

The findings of this study illustrate the complexity of RCH landscapes and the need for interdisciplinary approaches to elucidate the causal connections between historical land use, landform characteristics, soil properties and ecosystem processes. Future research should especially examine plant distribution differences over the year, within and outside RCHs, and examine within hearth specific patterns in soil morphology and chemistry.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

von Berg, C.H.E., 1860. Anleitung zum Verkohlen des Holzes: ein Handbuch für Forstmänner, Hüttenbeamte, Technologen und Cameralisten, 2nd ed. Eduard Zerin, Darmstadt.

Berg, T.M., 1978. Dickinson quadrangle. In: Pennsylvania Topographic and Geologic Survey, 166.

Beven, K.J., Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. Hydrol. Sci. Bull. 24, 43–69. https://doi.org/10.1080/02626667909491834.

Böhner, J., Selige, T., 2006. Spatial prediction of soil attributes using terrain analysis and climate regionalisation. In: SAGA - Analysis and Modelling Applications, 115, pp. 13–27.

Böhner, J., Köthe, R., Conrad, O., Gross, J., Ringeler, A., Selige, T., 2002. Soil regionalisation by means of terrain analysis and process parameterisation. In: Micheli, E., Nachtergaele, F., Montanarella, L. (Eds.), Soil Classification 2001. The European Soil Bureau, Joint Research Centre, Ispra, pp. 213–222.

Bond, J., 2007. Medieval charcoal-burning in England. In: Klápště, J., Sommer, P. (Eds.), Arts and Crafts in Medieval Rural Environment. Brepols Publishers, Turnhout, pp. 277–294.

Bonhage, A., Hirsch, F., Raab, T., Schneider, A., Raab, A., Ouimet, W., 2020a. Characteristics of small anthropogenic landforms resulting from historical charcoal production in western Connecticut, USA. Catena 195, 104896. https://doi.org/10.1016/j.catena.2020.104896.

Bonhage, A., Hirsch, F., Schneider, A., Raab, A., Raab, T., Donovan, S., 2020b. Long term anthropogenic enrichment of soil organic matter stocks in forest soils – detecting a legacy of historical charcoal production. For. Ecol. Manag. 459, 117814 https://doi.org/10.1016/j.foreco.2019.117814.

Borchard, N., Ladd, B., Eschemann, S., Hegenberg, D., Möseler, B.M., Amelung, W., 2014. Black carbon and soil properties at historical charcoal production sites in Germany. Geoderma 232–234, 236–242. https://doi.org/10.1016/j.geoderma.2014.05.007.

Bremner, J.M., 1996. Nitrogen-Total. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis, SSSA Book Series. Soil Science Society of America, American Society of Agronomy, Madison, WI, USA, pp. 1085–1121.

Burnham, M.B., Cumming, J.R., Adams, M.B., Peterjohn, W.T., 2017. Soluble soil aluminum alters the relative uptake of mineral nitrogen forms by six mature temperate broadleaf tree species: possible implications for watershed nitrate retention. Oecologia 327–337. https://doi.org/10.1007/s00442-017-3955-8.

Carrari, E., Ampoorter, E., Bussotti, F., Coppi, A., Nogales, A.G., Pollastrini, M., Verheyen, K., Selvi, F., 2018. Effects of charcoal hearth soil on forest regeneration: evidence from a two-year experiment on tree seedlings. For. Ecol. Manag. 37–44 https://doi.org/10.1016/j.foreco.2018.05.038.

Conrad, O., Bechtel, B., Bock, M., Dietrich, H., Fischer, E., Gerlitz, L., Wehberg, J., Wichmann, V., Böhner, J., 2015. System for Automated Geoscientific Analyses (SAGA) v. 2.1.4. Geosci. Model Dev. 8, 1991–2007. https://doi.org/10.5194/gmd-8-1991-2015.

Criscuoli, I., Alberti, G., Baronti, S., Favilli, F., Martinez, C., Calzolari, C., Pusceddu, E., Rumpel, C., Viola, R., Miglietta, F., 2014. Carbon sequestration and fertility after centennial time scale incorporation of charcoal into soil. PLoS One 9, 91114. https://doi.org/10.1371/journal.pone.0091114.

Cronan, C.S., April, R., Bartlett, R.J., Bloom, P.R., Driscoll, C.T., Gherini, S.A., Henderson, G.S., Joslin, J.D., Kelly, J.M., Parnell, R.A., Patterson, H.H., Raynal, D.J., Schaedle, M., Schofield, C.L., Sucoff, E.I., Tepper, H.B., Thornton, F.C., 1989. Aluminum toxicity in forests exposed to acidic deposition: the ALBIOS results. Water Air Soil Pollut. 48, 181–192. https://doi.org/10.1007/BF00282377.

Crutchley, S., Crow, P., 2010. The Light Fantastic: Using Airborne Lidar in Archaeological Survey. English Heritage, Swindon.

Decker, K.L., Boerner, R.E.J., 1997. Ca:Al ratio effects on growth and competitive interactions of Northern Red Oak (Quercus rubra) and Yellow-Poplar (Liriodendron tulipifera). J. Torrey Bot. Soc. 124, 286–296.

Donovan, S., Ignatiadis, M., Ouimet, W., Dethier, D., Hren, M., 2021. Gradients of geochemical change in relic charcoal hearth soils. CATENA 197, 104991. https://doi.org/10.1016/j.catena.2020.104991.

E.S.R.I, 2021a. 3D Analysis Toolkit. Environmental Systems Research Institute, Redlands, CA.

E.S.R.I, 2021b. ArcGIS Desktop: Release 10.6. Environmental Systems Research Institute, Redlands, CA.

Eckert, D., Sims, J.T., 2011. Recommended soil ph and lime requirement tests. In: Sims, J.T., A, W. (Eds.), Recommended Soil Testing Procedures for the Northeastern

United States. Northeast Regional Bulletin #493, Agricultural Experiment Station. University of Delaware, Newark, DE, pp. 19–25.

EPA, U.S, 1996. Method 3050B: Acid Digestion of Sediments, Sludges, and Soils. Revision 2.

EPA, U.S, 2014. Method 6010D (SW-846): Inductively Coupled Plasma-Atomic Emission Spectrometry.

Fink, C.M., Drohan, P.J., 2016. High resolution hydric soil mapping using LiDAR digital terrain modeling. Soil Sci. Soc. Am. J. 80 (2), 355–363.

Friedrich II, K., 1779. Verordnung, wie es mit dem Holzschlag zu Kohlen und Köhlereyen bei den königlichen Eisen=Blech=Kupfer=und auch anderen Hütten=und Hammerwerken gehalten werden soll. De Dato Berlin, den 18. Januar 1779. In: Kohlenschwelen in den kgl. Forsten und Holzschlag für Köhlereien bei den kgl. Hüttenund Hammerwerken (1738–1849), F.5-12: Brandenburgisches Landeshauptarchiv, Pr. Br. Rep. 2A III F Regierung Potsdam.

G.R.A.S.S. Development Team, 2019. Geographic Resources Analysis Support System (GRASS) Software, Version 7.6. Open Source Geospatial Foundation.

Garcia-Barreda, S., Molina-Grau, S., Forcadell, R., Sánchez, S., Reyna, S., 2017. Long-term soil alteration in historical charcoal hearths affects Tuber melanosporum mycorrhizal development and environmental conditions for fruiting. Mycorrhiza 27 (6), 603–609.

Gießelmann, U., Borchard, N., Traunspurger, W., Witte, K., 2019. Long-term effects of charcoal on nematodes and other soil meso- and microfaunal groups at historical kiln-sites – a pilot study. Eur. J. Soil Biol. 93, 103095 https://doi.org/10.1016/j.ejsobi.2019.103095.

Gordon, R.B., 2000. A Landscape Transformed: The Ironmaking District of Salisbury. Oxford University Press, Connecticut.

Groenewoudt, B., 2007. Charcoal burning and landscape dynamics in the early medieval Netherlands. In: Klápště, J., Sommer, P. (Eds.), Arts and Crafts in Medieval Rural Environment. Brepols Publishers, Turnhout, pp. 327–337.

Gruber, S., Peckham, S., 2008. Chapter 7: Land-Surface Parameters and Objects in Hydrology. In: Developments in Soil Science. Elsevier, pp. 171–194.

Hardy, B., Dufey, J.E., 2015. Les aires de faulde en forêt Wallonne: repérage, morphologie et distribution spatiale. forêt. Nature 135, 19–30.

Hardy, B., Cornelis, J.-T., Houben, D., Lambert, R., Dufey, J.E., 2016. The effect of pre-industrial charcoal kilns on chemical properties of forest soil of Wallonia, Belgium: effect of pre-industrial charcoal kilns on forest soil properties. Eur. J. Soil Sci. 67, 206–216. https://doi.org/10.1111/ejss.12324.

Hardy, B., Cornelis, J.-T., Houben, D., Leifeld, J., Lambert, R., Dufey, J.E., 2017. Evaluation of the long-term effect of biochar on properties of temperate agricultural soil at pre-industrial charcoal kiln sites in Wallonia, Belgium: effect of pre-industrial charcoal kilns on agricultural soil properties. Eur. J. Soil Sci. 68, 80–89. https://doi.org/10.1111/ejss.12395.

Hazell, Z., Crosby, V., Oakey, M., Marshall, P., 2017. Archaeological investigation and charcoal analysis of charcoal burning platforms, Barbon, Cumbria, UK. Quat. Int. 458, 178–199. https://doi.org/10.1016/j.quaint.2017.05.025.

Hennius, A., 2019. Spår av kolning arkeologiskt kunskapsunderlag och forskningsöversikt.

Hildebrandt, H., Heuser-Hildebrandt, B., Wolters, S., 2007. Kulturlandschaftsgenetische und Bestandesgeschichtliche Untersuchungen anhand von Kohlholzspektren aus historischen Meilerplätzen, Pollendiagrammen und archivalischen Quellen im Naturpark Pfälzerwald, Forstamt Johanniskreuz, Mainzer Geographische Studien, Sonderband 3, Mainz.

Hirsch, F., Raab, T., Ouimet, W., Dethier, D., Schneider, A., Raab, A., 2017. Soils on historic charcoal hearths: terminology and chemical properties. Soil Sci. Soc. Am. J. 81, 1427–1435. https://doi.org/10.2136/sssaj2017.02.0067.

Hirsch, F., Schneider, A., Bauriegel, A., Raab, A., Raab, T., 2018. Formation, classification, and properties of soils at two relict charcoal hearth sites in Brandenburg, Germany. Front. Environ. Sci. 6, 94. https://doi.org/10.3389/fenvs.2018.00094.

Hirsch, F., Schneider, A., Bonhage, A., Raab, A., Drohan, P.J., Raab, T., 2020. An initiative for a morphologic-genetic catalog of relict charcoal hearths from Central Europe. Geoarchaeology 35, 974–983. https://doi.org/10.1002/gea.21799.

Hoskins, D.M., 1976. McAlevys Fort quadrangle. In: Pennsylvania Topographic and Geologic Survey, 663, p. 368.

Hoskins, B.R., Erich, M.S., 2008. Modification of the Mehlich Lime Buffer Test. Commun. Soil Sci. Plant Anal. 39, 2270–2281. https://doi.org/10.1080/00103620802289372.

IUSS Working Group WRB, 2015. World Reference Base for Soil Resources 2014, update 2015 International soil classification system for naming soils and creating legends for soil maps. In: World Soil Resources Reports No. 106. FAO, Rome.

Jasiewicz, J., Stepinski, T.F., 2013. Geomorphons — a pattern recognition approach to classification and mapping of landforms. Geomorphology 182, 147–156. https://doi.org/10.1016/j.geomorph.2012.11.005.

Johanson, J., Brown, J., 2012. Ecological site development: accelerating the effort. Rangelands 34, 29–31. https://doi.org/10.2111/RANGELANDS-D-11-00068.1.

Johnson, K.M., Ouimet, W.B., Raslan, Z., 2015. Geospatial and LiDAR-based Analysis of 18th to Early 20th Century Timber Harvesting and Charcoal Production in Southern New England. Geological Society of America.

Kerré, B., Bravo, C.T., Leifeld, J., Cornelissen, G., Smolders, E., 2016. Historical soil amendment with charcoal increases sequestration of non-charcoal carbon: a comparison among methods of black carbon quantification: Historical charcoal enhances soil carbon sequestration. Eur. J. Soil Sci. 67, 324–331. https://doi.org/10.1111/ejss.12338.

Kerré, B., Willaert, B., Cornelis, Y., Smolders, E., 2017. Long-term presence of charcoal increases maize yield in Belgium due to increased soil water availability. Eur. J. Agron. 91, 10–15.

Klemm, S., 2005. Interdisziplinäre Untersuchungen von Kohlstätten aus Mittelalter und Neuzeit in der Eisenerzer Ramsau, Steiermark. Archaeol. Austriaca, 89, pp. 269–330. https://doi.org/10.1553/archaeologia89s269.

Lasota, J., Błońska, E., Babiak, T., Piaszczyk, W., Stępniewska, H., Jankowiak, R., Boroń, P., Lenart-Boroń, A., 2021. Effect of charcoal on the properties, enzyme activities and microbial diversity of temperate pine forest soils. Forests 12, 1–24. https://doi.org/10.3390/f12111488.

Ludemann, T., Nelle, O., 2002. Die Wälder am Schauinsland und ihre Nutzung durch Bergbau und Köhlerei, Schriftenreihe Freiburger forstliche Forschung CN - SD196. S33 L83 2002. In: Forstliche Versuchs- und Forschungsanstalt Baden-Württemberg. Abteilung Botanik und Standortskunde, Freiburg.

Marr, P.G., Wah, J.S., 2019. Remote identification of cultural features on the landscape: assessing the accuracy of using lidar to detect charcoal hearth platforms. Archaeol. East. North Am. 47, 51–62.

Mattivi, P., Franci, F., Lambertini, A., Bitelli, G., 2019. TWI computation: a comparison of different open source GISs. In: Open Geospatial Data, Software and Standards, 4, pp. 1–12.

Mikan, C.J., Abrams, M.D., 1995. Altered forest composition and soil properties of historic charcoal hearths in southeastern Pennsylvania. Can. J. For. Res. 25, 687–696. https://doi.org/10.1139/x95-076.

Mikan, C.J., Abrams, M.D., 1996. Mechanisms inhibiting the forest development of historic charcoal hearths in southeastern Pennsylvania. Can. J. For. Res. 26, 1893–1898. https://doi.org/10.1139/x26-213.

Minitab, Inc, 2020. Minitab 19 Statisitcal Software. State College, Pennsylvania.

Moore, I.D., Grayson, R.B., Ladson, A.R., 1991. Digital terrain modelling: a review of hydrological, geomorphological, and biological applications. Hydrol. Process. 5, 3–30. https://doi.org/10.1002/hyp.3360050103.

Nelson, D.W., Sommers, L.E., 1996. Total carbon, organic carbon, and organic matter. In: Sparks, D.L., Page, A.L., Helmke, P.A., Loeppert, R.H., Soltanpour, P.N., Tabatabai, M.A., Johnston, C.T., Sumner, M.E. (Eds.), Methods of Soil Analysis, SSSA Book Series. Soil Science Society of America, American Society of Agronomy, Madison, WI, USA, pp. 1085–1121.

NOAA National Centers for Environmental information, 2022. Climate at a Glance: County Mapping. published June. retrieved on July 8, 2022 from. https://www.ncei.noaa.gov/cag/.

PAMAP Program, PA Department of Conservation and Natural Resources, Bureau of Topographic and Geologic Survey, 2006. PAMAP Program 3.2 ft Digital Elevation Model of Pennsylvania [WWW Document]. Pennsylvania Spatial Data Access. URL. https://www.pasda.psu.edu/.

Pennsylvania Department of Conservation and Natural, 2021a. History of Greenwood Furnace State Park [WWW Document]. URL. https://www.dcnr.pa.gov/StateParks/FindAPark/GreenwoodFurnaceStatePark/Pages/History.aspx.

Pennsylvania Department of Conservation and Natural, 2021b. History of Pine Grove Furnace State Park.

Petraitis, P., 2013. Multiple Stable States in Natural Ecosystems. Oxford University Press.

Potter, N., Brubaker, K., 2013. Lidar reveals thousands of 18th and 19th century charcoal hearths on South Mountain. In: South-Central Pennsylvania, in: 48th Annual Meeting. The Geologic Society of America.

Quinn, P., Beven, K., Chevallier, P., Planchon, O., 1991. The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. Hydrol. Process. 5, 59–79. https://doi.org/10.1002/hyp.3360050106.

Raab, A., Takla, M., Raab, T., Nicolay, A., Schneider, A., Rösler, H., Heußner, K.-U., Bönisch, E., 2015. Pre-industrial charcoal production in Lower Lusatia (Brandenburg, Germany): Detection and evaluation of a large charcoal-burning field by combining archaeological studies, GIS-based analyses of shaded-relief maps and dendrochronological age determination. Quat. Int. 367, 111–122. https://doi.org/10.1016/j.quaint.2014.09.041.

Raab, T., Hirsch, F., Ouimet, W., Dethier, D., 2016. Soil stratigraphy of charcoal kiln remains (CKR) in the Litchfield Hills. In: EGU General Assembly Conference Abstracts. CT, USA, pp. 2016–3477.

Raab, T., Hirsch, F., Ouimet, W., Johnson, K.M., Dethier, D., Raab, A., 2017. Architecture of relict charcoal hearths in northwestern Connecticut, USA. Geoarchaeology 32, 502–510. https://doi.org/10.1002/gea.21614.

Raab, T., Raab, A., Bonhage, A., Schneider, A., Hirsch, F., Birkhofer, K., Drohan, P.J., Wilmking, M., Kreyling, J., Malik, I., Wistuba, M., van der Maaten-Theunissen, E., van der Maaten-Theunissen, M., Urich, T., 2022. Do small landforms have large effects? A review on the legacies of pre-industrial charcoal burning. Geomorphology 413. https://doi.org/10.1016/j.geomorph.2022.108332.

Ratajczak, Z., Carpenter, S.R., Ives, A.R., Kucharik, C.J., Ramiadantsoa, T., Stegner, M.A., Williams, J.W., Zhang, J., Turner, M.G., 2018. Abrupt change in ecological systems: inference and diagnosis. Trends Ecol. Evol. 33, 513–526. https://doi.org/10.1016/j.tree.2018.04.013.

Rolando, V.R., 1992. 200 Years of Soot and Sweat: The History and Archeology of Vermont's iron, Charcoal, and Lime Industries. Vermont Archaeological Society.

Ross, D., Ketterings, Q., 2011. Recommended soil tests for determining soil cation exchange capacity. In: Sims, J.T., A, W. (Eds.), Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493, Agricultural Experiment Station. University of Delaware, Newark, DE, pp. 75–86.

Rutkiewicz, P., Malik, I., Wistuba, M., Osika, A., 2019. High concentration of charcoal hearth remains as legacy of historical ferrous metallurgy in southern Poland. Quat. Int. 512, 133–143. https://doi.org/10.1016/j.quaint.2019.04.015.

Sasaki, T., Furukawa, T., Iwasaki, Y., Seto, M., Mori, A.S., 2015. Perspectives for ecosystem management based on ecosystem resilience and ecological thresholds against multiple and stochastic disturbances. Ecol. Indic. 57, 395–408. https://doi.org/10.1016/j.ecolind.2015.05.019.

Scheffer, M., 2009. Critical Transitions in Nature and Society. Princeton University Press.

Schneider, A., Hirsch, F., Raab, A., Raab, T., 2018. Dye tracer visualization of infiltration patterns in soils on relict charcoal hearths. Front. Environ. Sci 6, 143. https://doi.org/10.3389/fenvs.2018.00143.

Schneider, A., Bonhage, A., Raab, A., Hirsch, F., Raab, T., 2020a. Large-scale mapping of anthropogenic relief features—legacies of past forest use in two historical charcoal production areas in Germany. Geoarchaeology 35, 545–561. https://doi.org/10.1002/gea.21782.

Schneider, A., Hirsch, F., Bonhage, A., Raab, A., Raab, T., 2020b. The soil moisture regime of charcoal-enriched land use legacy sites. Geoderma 366, 114241. https://doi.org/10.1016/j.geoderma.2020.114241.

Schneider, A., Bonhage, A., Hirsch, F., Raab, A., Raab, T., 2022. Hot spots and hot zones of soil organic matter in forests as a legacy of historical charcoal production. For. Ecol. Manag. 504, 119846 https://doi.org/10.1016/j.foreco.2021.119846.

Soil Survey Staff, U.S. Department of Agriculture, Natural Resources Conservation Service, 2014a. Soil Survey Geographic (SSURGO) database for Cumberland County, Pennsylvania. Fort Worth, Texas. Accessed 06/22/2021.

Soil Survey Staff, U.S. Department of Agriculture, Natural Resources Conservation Service, 2014b. Soil Survey Geographic (SSURGO) database for Huntingdon County, Pennsylvania. Fort Worth, Texas. Accessed 06/22/2021.

Standish, R., Hobbs, R., Mayfield, M., Bestelmeyer, B., Suding, K., Battaglia, L., Eviner, V., Hawkes, C., Temperton, V., Harris, V., Funk, J., Thomas, P., 2014. Resilience in ecology: abstraction, distraction, or where the action is? Biol. Conserv. 177, 43–51. https://doi.org/10.1016/j.biocon.2014.06.008.

Stolz, C., Grunert, J., 2010. Late Pleistocene and Holocene landscape history of the Central Palatinate forest (Pfälzerwald, South-Western Germany). Quat. Int. 222, 129–142. https://doi.org/10.1016/j.quaint.2009.08.022.

Straka, T.J., 2014. Historic charcoal production in the us and forest depletion: development of production parameters. Adv. Hist. Stud. 03, 104–114. https://doi.org/10.4236/ahs.2014.32010.

Straka, T.J., 2017. Charcoal as a fuel in the ironmaking and smelting industries. Adv. Hist. Stud. 6, 56–64. https://doi.org/10.4236/ahs.2017.61004.

Suding, K.N., Gross, K.L., 2006. The dynamic nature of ecological systems: multiple states and restoration trajectories. In: Falk, D.A., Palmer, M.A., Zelder, J.B. (Eds.), Foundations of Restoration Ecology. Island Press, Washington, D.C, pp. 190–209.

Swieder, A., 2019. Meilerrelikte als Teil der archäologischen Kulturlandschaft im östlichen Harz. In: Raab, T., Raab, A., Schopper, F. (Eds.), Erfassung und Bewertung von vorindustriellen Meilerstandorten - Workshop 19. Februar 2019, 8. Geopedology and Landscape Development Research Series, pp. 43–70. https://doi.org/10.26127/BTUOpen-4817.

Tolksdorf, J.F., Kaiser, K., Petr, L., Herbig, C., Kočár, P., Heinrich, S., Wilke, F.D.H., Theuerkauf, M., Fülling, A., Schubert, M., Schröder, F., Křivánek, R., Schulz, L., Bonhage, A., Hemker, C., 2020. Past human impact in a mountain forest: geoarchaeology of a medieval glass production and charcoal hearth site in the Erzgebirge, Germany. Reg. Environ. Chang 20, 71. https://doi.org/10.1007/s10113-020-01638-1.

U S Geological Survey, 2017a. USGS QL2 LiDAR for Adams County, PA 2017 [WWW Document]. Pennsylvania Spatial Data Access. URL. https://www.pasda.psu.edu/.

U S Geological Survey, 2017b. USGS QL2 LiDAR for Cumberland County, PA 2017 [WWW Document]. Pennsylvania Spatial Data Access. URL. https://www.pasda.psu.edu/.

U S Geological Survey, 2017c. USGS QL2 LiDAR for Franklin County, PA 2017 [WWW Document]. Pennsylvania Spatial Data Access. URL. https://www.pasda.psu.edu/.

Waltman, W.J., 1997. Soil climate regimes of Pennsylvania. In: Penn State Agricultural Experiment Station bulletin (USA).

Wang, L., Liu, H., 2006. An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. Int. J. Geogr. Inf. Sci. 20, 193–213. https://doi.org/10.1080/13658810500433453.

Wohl, E., 2015. Legacy effects on sediments in river corridors. Earth-Sci. Rev. 147, 30–53. https://doi.org/10.1016/j.earscirev.2015.05.001.

Wolf, A., Beegle, D., 2011. Recommended Soil Tests for Macro and Micronutrients. In: Sims, J.T., A, W. (Eds.), Recommended Soil Testing Procedures for the Northeastern United States. Northeast Regional Bulletin #493, Agricultural Experiment Station. University of Delaware, Newark, DE, pp. 39–47.

Wolf, A.M., Beegle, D.B., Hoskins, B., 2008. Comparison of Shoemaker–McLean–Pratt and Modified Mehlich Buffer Tests for Lime Requirement on Pennsylvania Soils. Commun. Soil Sci. Plant Anal. 39, 1848–1857. https://doi.org/10.1080/00103620802073834.

Wood, J., 1997. The Geomorphological Characterization of Digital Elevation Models. University of Leicester (United Kingdom).