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Soils on Historic Charcoal Hearths: Terminology and Chemical Properties

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Historic charcoal hearth remains provide a unique archive of the long-term interaction between biochar, soil development, and plant growth. Charcoal as raw material was crucial for production of iron in iron works, and hence numerous charcoal hearths can be found in the forests near historic iron works in Europe and in the eastern United States. Charcoal hearths are round to elliptical forms often around 10 m in diameter and consist of several-decimeter-thick layers that contain charcoal fragments, ash, and burnt soil. We studied the soil chemistry of 24 charcoal hearths and compared them with the surrounding "natural" soils in the northern Appalachians of northwestern Connecticut. The thickness of the topsoils on the charcoal hearths and their carbon content are remarkably higher than in the surrounding topsoils. The presence of residual products from charcoal production classifies the soils as Anthropic Udorthents (US Soil Taxonomy) or Spolic Technosols (Humic) according to the World Reference Base for Soil Resources. The widespread occurrence of charcoal hearth remains, and their high spatial density in different ecosystems underlines their importance for further pedological research.

Abbreviations: PyOM, pyrogenic organic matter; SOM, soil organic matter; WRB, IUSS Working Group World Reference Base.

Significant disturbances of the soil landscape by ancient land use are seen mostly as a result of agriculture, whereas forestry is considered to have a comparatively minor effect (Dotterweich, 2013). During the early periods of silviculture, charcoal burning was of great importance to feed energy-intensive and rapidly developing economies at the beginning of the industrial revolution (Weetmann, 2000; Williams, 1989). Clearing, subsequent afforestation, and changing tree vegetation are well-known effects of charcoal production (Straka, 2014). The remains of charcoal mounds (Raab et al., 2017) and the subsurface implications of charcoal burning, especially the alteration of soil properties, are a legacy of historic charcoal production (Borchard et al., 2014; Powell et al., 2012). Peaking between the 17th and 20th century in Europe (Bond, 2007; Deforce et al., 2013; Hesse, 2013) and North America (Hart et al., 2008; Potter et al., 2013), brittle charcoal was produced in the forest mainly near iron works (Gordon, 1996; Raab et al., 2014). Charcoal production in such areas was an extensive and decentralized business, with loggers cutting the forests for logs and colliers stacking up these logs on leveled round platforms to form charcoal hearths.

The production of charcoal plays an important role only in local economies in some parts of Africa and Asia (Bolognesi et al., 2015; Chidumayo and Gumbo, 2013). In Europe in Medieval and Roman times and before, charcoal was produced mainly in charcoal pits that were dug into the ground (Groenewoudt, 2005), but later the term "charcoal pit" was also used synonymously for completely above-

Core Ideas

- **Charcoal hearth remains are a widespread legacy of historic iron production.**
- **Soils on charcoal hearth remains are a carbon sink.**
- **Soils on charcoal hearths are classified as Anthropic Udorthents.**

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ground charcoal production sites (Bond, 2007; Kemper, 1941). Until the end of the 19th century, charcoal hearths, sometimes also termed charcoal pits, charcoal mounds, or charcoal kilns, where the logs were stacked above ground and covered with earthen material, were used for charring (Bond, 2007; Straka, 2014), but subsequently charring in brick-built structures replaced the former technique. In contrast to charcoal kilns, which have a masonry structure and were used multiple times, charcoal hearth sites were earthen and less permanent, with use ranging from once to multiple times. In some cases, charcoal hearth sites were reoccupied >25 yr after initial use after forest regrowth. Whereas in charcoal kilns ash and remaining charcoal fragments are removed before the next use, these materials usually remain at charcoal hearth sites after the charcoal harvesting. Today, relict charcoal hearth sites are characterized by a platform resulting from site preparation and a mound consisting of the residues of the material used to cover the wood stack and any material left behind after charcoal production. Relict charcoal hearth sites generally contain charcoal fragments and substrate directly or indirectly influenced by charcoal production, often thermally transformed minerals or biomass. Sites with multiple uses are characterized by a platform from the original construction and subsequent resurfacing and the charcoal remains associated with the charcoaling process. Depending on the topography, the diameter of these platforms ranges between 8 and 20 m, with the largest charcoal hearths in flatlands. Charcoal hearth sites occur in high numbers and spatial density in forest areas near historic industry sites in North America and in Europe, with up to several thousand kiln sites related to a single iron work (Johnson et al., 2015; Raab et al., 2014). On charcoal hearths, soils are not only directly affected by pyrolysis (Aldeias et al., 2016) but also are enriched with ash and with the byproducts of the charring (Borchard et al., 2014; Knicker, 2011).

In Litchfield County in northwestern Connecticut, more than 20,000 charcoal hearths in an area of 1170 km^2 have been mapped recently using airborne laser scanning data (Johnson et al., 2015). The large number of charcoal hearths in this region is due to historic iron production, with the founding of the first furnace in 1762, peaking around 1850, and extending to the late 19th Century (Gordon, 2001; Raab et al., 2017). To support this industry, forests in Litchfield County were divided into blocks ranging from 50 to several hundred acres in size and dedicated for charcoal production; some blocks were cut successively up to five times. Oak and chestnut were used in Litchfield County for the production of charcoal (Harris, 1885). The second growth was gained from coppicing (Schwarz, 1907); the time interval between the cutting was between 20 and 35 yr (Winer, 1955).

Ecological succession and soil development took over after charcoal hearths sites were abandoned. Due to the charring and site preparation, the substrate of the charcoal hearth is enriched with soil organic matter (SOM) and pyrogenic organic matter (PyOM) consisting of diverse aromatic carbon compounds (Knicker, 2011). The carbon content of charcoal hearths has not been included in the calculations for the total carbon pool of soils (Batjes, 1996; Scharlemann et al., 2014). Due to the abundance and wide distribution of charcoal hearths, their occurrence in different ecosystems, the range of ages, and the persistence of PyOM, charcoal hearth sites have the potential for enriching ongoing discussions about the longer-term influence of biochar in soils. The architecture, usage, and geoarchaeological background of relict charcoal hearths in Connecticut recently have been described by Raab et al. (2017). In this study we focus on the soil properties of the sites. We characterize the soils of representative charcoal hearths in a region of historic charcoal production in northeastern United States by identifying and classifying their soil stratigraphy and by describing the soil chemistry outside vs. inside of the relict charcoal hearths and comparing them with published data from charcoal hearths in Europe.

METHODS

Our study area is situated in Litchfield County, CT (Fig. 1), where glacial sediments from the Wisconsinan glaciation overlie the bedrock of the northern Appalachian Mountains (Stone et al., 2005). The lithology and texture of glacial deposits are diverse, although clasts of local metamorphic bedrock and loamy gravels are abundant. The climate is temperate (mean annual temperature, 7.2–8.3°C; average annual precipitation, 1200–1350 mm), and most parts of the landscape are covered with deciduous forests (e.g., maple, oak, birch, aspen).

We focused on three different sites covered with deciduous forest and sampled eight characteristic charcoal hearths at each site. Coring was done with a 1-m hand corer driven down into the subsoil. On the partially multilayered charcoal hearths, all the substrate above the natural subsoils was taken as a composite sample. Outside of the charcoal hearths, only the substrate from the topsoil was sampled. For each site, bulk samples were composited from six cores outside and the six cores on the charcoal hearth, respectively. In total, 24 charcoal hearths were sampled, each with six cores evenly placed on the charcoal mound and with six cores collected in a circular pattern 10 m outside the charcoal hearth (Fig. 2b). In addition, soils were described based on hand-dug trenches at two representative charcoal hearths according to the US Soil Taxonomy (Soil Survey Staff, 2014) and the World Reference Base for Soil Resources (IUSS Working Group World Reference Base [WRB], 2014). Volumetric samples were taken in the soil pits in metal boxes with a fixed volume of 176 mL. The bulk density of these volumetric samples was calculated after drying at 105°C until a constant weight was reached. Soil color was determined in the laboratory on moist samples with a Munsell Soil Color Chart. Grain size analyses were done according to the Soil Survey Investigation Report No. 42 method 3A1a1a but with wet sieving instead of dry sieving.

All samples for chemical analyses were dried at 40°C. Soil pH was determined potentiometrically with a ratio of 1:2 in 0.01 M $CaCl_2$. The total carbon, nitrogen, and sulfur concentrations were analyzed on ground samples by gas chromatography by high-temperature heating with a vario EL cube analyzer. We estimated the PyOM concentration mathematically using the total

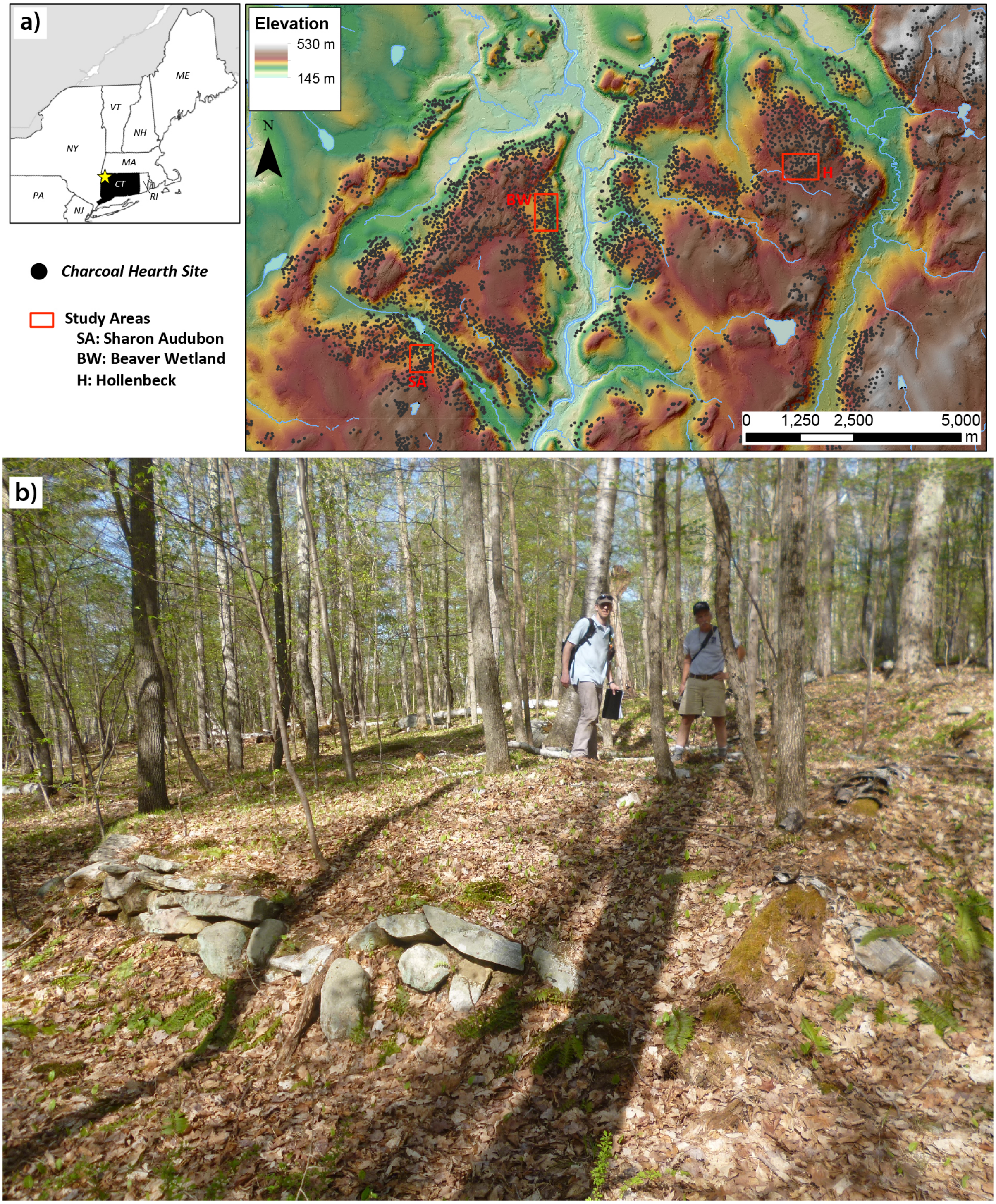

Fig. 1. (a) Location of the study sites. (b) View looking upslope at a historic charcoal hearth. The boulders were placed by the colliers on the downslope end to stabilize the platform.

carbon concentration and by subtracting the carbon concentration of the soil samples taken on the charcoal hearth from the carbon concentration of the topsoil outside the charcoal hearth.

RESULTS AND DISCUSSION

Based on morphology and laboratory analysis, soils outside of the charcoal hearths are classified as Typic Dystrudepts (Fig. 3A) according to US Soil Taxonomy and Cambisols according to the WRB. The topsoil is intensely rooted and has a grayish brown color (10 YR 4/2). The cambic horizon has a more reddish to yellow brown color (6.25 YR 4/6 to 7.5 YR 4/3.5) and a blocky soil structure. The texture of the Typic Dystrudepts is a sandy loam, dominated by fine sand (around 25%) and decreasing clay content with depth (Table 1).

The charcoal hearths in our study site were built as round to elliptical platforms 10 m in diameter on slopes of 6° to 17°. Coring and trenching of the charcoal hearths revealed that the platform of the charcoal hearth consists of a wedge-like and

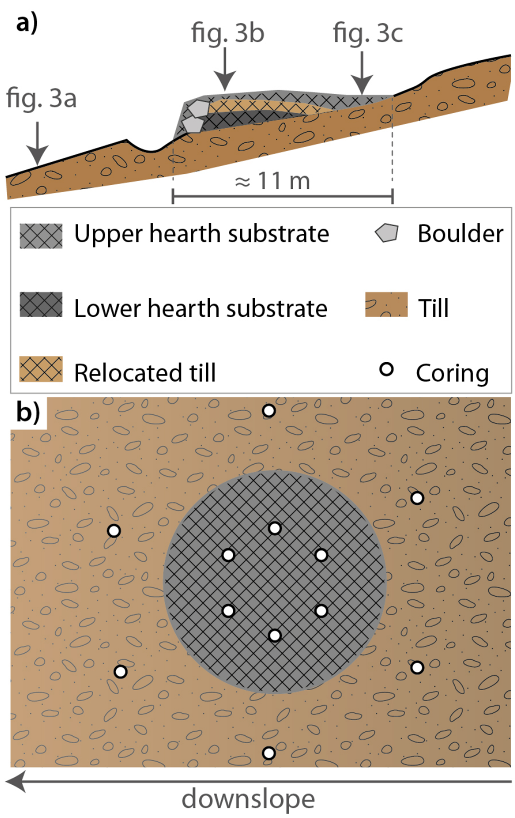

Fig. 2. (a) Cross-section architecture of a representative charcoal hearth based on trenching and coring. (b) Map view sketch of the sampling approach with the location of the six cores outside and on the charcoal hearth.

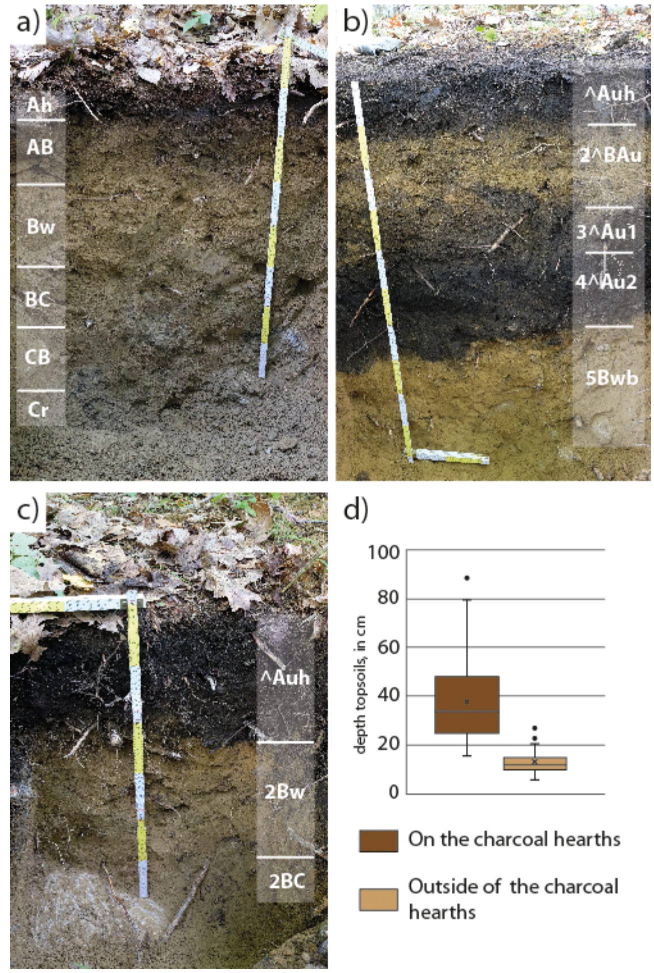

Fig. 3. Photographs and soil profile descriptions for sites outside of the charcoal hearth (a) and on the charcoal hearth (b and c). The position of the soil profiles is illustrated in Fig. 2a. (b) Multilayered soils typical for the downslope position of charcoal hearths. (c) Soil profile typical for the upslope position of charcoal hearths. (d) Summary of topsoil thickness (A, Au units) on the charcoal hearths and outside based on 144 core locations.

multilayered sediment complex (Fig. 2a) with a two-layered stratigraphy in the upslope direction (Fig. 3c) and a four-layered stratigraphy in the downslope direction (Fig. 3b). Where the substrate of the charcoal hearth is multilayered and exceeds 50 cm, soils are classified as Anthroportic Udorthents (US Soil Taxonomy) and as Spolic Technosol (Humic, Thaptotransportic) over Cambisol (WRB). Otherwise, the soils on the charcoal hearths are classified as Anthropic Udorthents (US Soil Taxonomy) and as Spolic Technosols (Humic) over Cambisols according to the WRB. Due to the presence of human-made charcoal, the designation of a pretic horizon (IUSS Working Group WRB, 2014) is possible, but because charcoal hearths are related to an industrial-scale production rather than a product of agricultural usage, the diagnostic feature for the so-called "Terra Preta de Indio" (Glaser et al., 2000), we recommend the classification as a Technosol.

Topsoil on the charcoal hearth sites has a black to very dark gray color (10 YR 2.5/1), a high content of charcoal fragments in the fine soil fraction, and larger charcoal fragments (mainly charred branches). It is intensely rooted and enriched with organic matter. The soil has a granular soil structure, but with increasing depth a single grain structure dominates. Due to the architecture and stratigraphy of the charcoal hearths, we could distinguish at least two separate usages with an upper hearth substrate and an older lower hearth substrate separated by a

Table 1. Texture from the soil pit outside of charcoal hearth 16.

Site	Very coarse sand	Coarse sand	Medium sand	Fine sand	Very fine sand	Sand	Coarse silt	Fine silt	Silt	Clay	Texture (USDA)
	weight percent										
CT 6–2	3.6	5.0	9.8	22.7	15.3	56.4	16.3	14.2	30.5	13.1	sandy loam
CT 6–3	2.7	5.6	12.8	24.0	14.7	59.7	16.8	15.6	32.4	7.8	sandy loam
CT 6–4	3.7	5.9	14.6	25.6	14.6	64.4	16.3	11.6	27.9	7.7	sandy loam
CT 6–5	3.5	7.6	14.8	25.2	15.4	66.5	12.3	15.2	27.5	6.1	sandy loam
CT 6–6	3.8	5.5	13.0	25.4	16.8	64.4	14.7	13.3	28.0	7.6	sandy loam
CT 6–7	3.0	6.0	13.8	25.3	16.6	64.6	16.3	13.8	30.1	5.3	sandy loam

layer of redistributed sediment (Fig. 2a). The lower hearth substrate has a high content of charcoal fragments and is a preferred zone for rooting. The amount of time between the two usages remains open; historic records indicate that there might be about 20 to 35 yr for forest regrowth between the usages (Winer, 1955) or just days or weeks when the colliers operated several charcoal hearths repeatedly at the same time to char the wood from one clear cut (Straka, 2014). The wedge-like layer of relocated substrate (Fig. 2a and 2^BAu in Fig. 3b) can be interpreted as being a result of the preparation of a new platform for a second usage of the charcoal hearth site (Raab et al., 2017). In situ formation of this wedge-like layer by pedogenic processes can be excluded; we found no indications for podsolization or lessivage-like eluvial or illuvial features. According to the interpretation from Raab et al. (2017), the colliers raked substrate from upslope along the old platform to build a new and stable platform with noninflammable substrate on top. An erosive origin of the substrate by slopewash from upslope was discussed by Stolz and Grunert (2010) and Hildebrandt et al. (2007), but, because historic instructions from Germany for charcoal production on hillslopes (von Berg, 1860) explicitly prescribe the preparation of a former charcoal hearth for further reuse by applying a cover of fresh substrate, we favor a purposeful application.

Table 2. Soil data from soil pits at charcoal hearth 16.

Site	Depth	Horizon	SOM and/or PyOM†	C	N	S	Soil acidity (pH)	Bulk density
	cm			———	g kg^{-1}	———		g cm^{-3}
Soil pit on the charcoal hearth in downslope position (Fig. 3b)								
CT 3–1	0–6	^Auh1	SOM + PyOM	72.23	2.10	1.35	4.21	n.a.
CT 3–2	6–12	^Auh2	SOM + PyOM	65.67	1.79	0.89	4.30	0.70
CT 3–3	12–20	^Auh3	SOM + PyOM	16.81	0.41	1.08	4.63	n.a.
CT 3–4	20–28	2^BAb1	SOM + PyOM	17.96	0.39	0.88	4.75	n.a.
CT 3–5	28–35	2^BAb2	SOM + PyOM	24.97	0.66	0.83	4.88	n.a.
CT 3–6	35–43	2^BAb3	SOM + PyOM	31.91	0.72	0.78	4.94	n.a.
CT 3–7	43–50	3^Aub11	SOM + PyOM	54.25	1.10	0.65	4.98	n.a.
CT 3–8	50–57	3^Aub12	SOM + PyOM	55.56	1.26	0.74	5.04	n.a.
CT 3–9	57–68	4^Aub21	SOM + PyOM	42.92	0.97	0.68	5.03	n.a.
CT 3–10	68–70	5Bwb1	SOM only	10.57	0.42	0.96	5.17	n.a.
CT 3–11	70–79	5Bwb2	SOM only	6.59	0.13	0.72	5.17	n.a.
CT 3–12	79–88	5Bwb3	SOM only	4.53	0.07	0.94	5.25	n.a.
CT 3–13	88–100	5Bwb4	SOM only	5.24	0.09	0.79	5.20	n.a.
Soil pit on the charcoal hearth in upslope position (Fig. 3c)								
CT 4–1	0–6	^Auh1	SOM + PyOM	90.77	2.92	1.10	4.07	n.a.
CT 4–2	6–12	^Auh2	SOM + PyOM	77.78	1.96	0.87	4.20	0.76
CT 4–3	12–18	^Auh3	SOM + PyOM	62.87	1.66	0.82	4.43	n.a.
CT 4–4	18–25	^Auh4	SOM + PyOM	57.69	1.42	0.78	4.52	n.a.
CT 4–5	25–28	2Bw1	SOM only	13.26	0.33	0.81	4.78	n.a.
CT 4–6	28–45	2Bw2	SOM only	4.46	0.03	0.75	4.76	n.a.
CT 4–7	45–60	2BC	SOM only	4.93	b.d.l.	0.77	4.87	n.a.
Soil pit outside of the charcoal hearth (Fig. 3a)								
CT 6–1	0–3	Ah	SOM only	119.83	5.07	1.59	3.32	n.a.
CT 6–2	3–14	AB	SOM only	22.38	0.97	1.09	4.19	1.00
CT 6–3	14–27	Bw	SOM only	7.38	0.17	0.91	4.46	n.a.
CT 6–4	27–40	Bw	SOM only	5.08	0.08	0.83	4.58	n.a.
CT 6–5	40–55	BC	SOM only	3.83	b.d.l.	0.81	4.73	n.a.
CT 6–6	55–70	CB	SOM only	2.19	b.d.l.	0.62	4.74	n.a.
CT 6–7	70–80	Cr	SOM only	2.27	b.d.l.	0.68	4.78	n.a.

† PyOM, pyrogenic organic matter; SOM, soil organic matter.

The 2^BAu is heterogeneous, depending on the carbon concentration (Table 2). The color ranges from dark yellowish brown to very dark grayish brown (10 YR 4/4 to 10 YR 2.5/1.5) but is always darker than the 5Bwb, with its reddish yellow to brown color (6.25 YR 4/6 to 7.5YR 4/3.5) that is unaffected by charring.

The shape of the wedge-like charcoal hearth substrate, with thickness increasing in the downslope direction, might control water infiltration and water flow patterns or behavior on the charcoal hearth. Especially the vertical flow component and the percolation of soil water in the fossilized soil below may be affected. Abrupt changes of the substrate at layer boundaries may influence the percolation of soil water (Flury et al., 1994), and the sloped lower boundary of the hearth substrate is therefore prone to induce lateral flow rather than vertical flow. Therefore, site conditions for plant growth may be primarily controlled by soil physical properties rather than by bulk chemistry and nutrient status. In spite of higher nutrient availability in the hearth topsoil, significantly lower plant growth on hearth sites occurs on charcoal hearth sites reported in Pennsylvania and in northern Italy (Carrari et al., 2016; Mikan and Abrams 1996).

Concentrations of nitrogen and carbon significantly differ between the approximately 150-yr-old charcoal hearths (Raab et al., 2017) and the surrounding undisturbed soils, but sulfur concentrations do not vary between the sites (Fig. 4). The sulfur concentration of the topsoil is generally low (Fig. 4d), which can be explained by the naturally low sulfur concentrations of the forest soils. The carbon concentration in the charcoal hearth soil in Connecticut is on average 1.4 times higher than that of the soil in the vicinity (Fig. 4a). Similar ratios have been reported for charcoal hearth soils in Belgium in forests and under agricultural use. Although the carbon cannot be differentiated into SOM and PyOM by our results from flash combustion, we can infer the PyOM of the topsoils on charcoal hearths by comparing them with the topsoils outside of the charcoal hearth. For forest soils in a temperate climate, the turnover time for SOM ranges between less than 1 yr and decades (Taneva et al., 2006; Trumbore, 2000). Considering a time frame of at least 150 yr from the usage of the charcoal hearths until today, we can infer from the balance between the total carbon concentrations of the

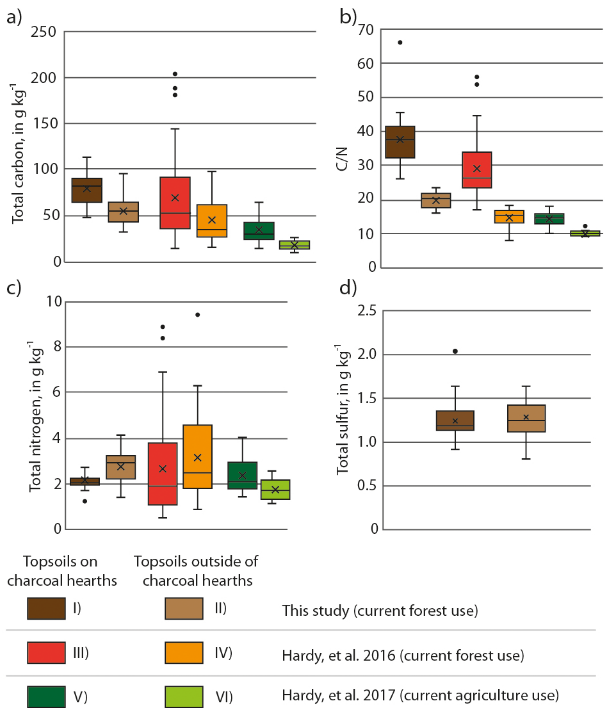

Fig. 4. (a) Total carbon content, (b) C/N ratio, (c) total nitrogen content, and (d) total sulfur content of topsoils from Connecticut and Belgium. Classes: (I) Bulk samples from the topsoils on the charcoal hearths and (II) outside of the charcoal hearths in Connecticut (*n* = 24, this study; data in Table 1); (III) bulk samples from the topsoils on the charcoal hearths in Belgium (*n* = 41) and (IV) outside of charcoal hearths in Belgium (*n* = 24; data from Hardy et al. [2016]); (V) topsoils on charcoal hearths in Belgium, agricultural use (*n* = 17); and (VI) outside of charcoal hearths (fixed sampling depth: 0–25 cm; *n* = 17; data from Hardy et al. [2017]).

hearth site topsoils as compared with the surrounding topsoils an average PyOM concentration of 23.8 ± 1.9 g kg^{-1} for the hearth topsoils. This accounts for 30% of their total carbon concentration (Supplemental Table S1). For charcoal hearth remains in Belgium, an average of 13.45 g kg^{-1} PyOM (calculated with data from Hardy et al. [2017]) was reported for sites on agricultural soils, and an average of 24 g kg^{-1} of PyOM (calculated with data from Hardy et al. [2017]) was reported for forested sites. Based on an average volume of 25 m^3 for the remains of a 10-m charcoal hearth in Litchfield County (Raab et al., 2017), an average bulk density of 0.73 g cm^{-3} (Table 2), and an average total carbon concentration of 79.57 g kg^{-1}, we calculate that a 10-m charcoal hearth relict contains 1.4×10^6 g carbon (SOM and PyOM).

Although the charcoal hearths contain more nitrogen than the surrounding topsoils due to the larger thickness of charcoal hearth substrate (Table 2), the total nitrogen concentration per unit soil mass of the charcoal hearth in Connecticut is lower than that of the surrounding topsoils (Fig. 4c; Supplemental Fig. S1). This is a result of the thicker topsoils on the charcoal hearth because the enrichment of nitrogen diminishes with increasing depth (Table 2). The lower nitrogen concentrations of the charcoal hearths in Connecticut also result in a more variable C/N ratio. These findings agree with charcoal hearths at forestry sites in Belgium (Hardy et al., 2016), which also have lower nitrogen concentrations in the substrate from the charcoal hearths and a scattered C/N ratio. For topsoils from charcoal hearths under agricultural use in Belgium, higher nitrogen concentrations than in the surrounding soils have been reported (Hardy et al., 2017). These higher nitrogen concentrations can be explained by a fertilizing effect from the charcoal admixture that also increases the sorption capacity. However, the comparison might be biased due to the fixed sampling depth of 25 cm in the Belgian study on agricultural sites.

Soil pH in the topsoil of the charcoal hearth in Connecticut ranges from 4.07 to 4.63 (Table 2). Outside of the charcoal hearth, the topsoil has a slightly lower pH (pH 3.32 and pH 4.19). This is most probably caused by the higher organic matter content of the charcoal hearth soil, promoting variable charge buffering (Knicker, 2011; Schwertmann et al., 1987). A slightly lower acidity of the charcoal hearth topsoil has also been noted for sites on acidic soils in Pennsylvania (Mikan and Abrams, 1995), New York (Hesson, 2016), Belgium (Hardy et al., 2016), and Germany (Borchard et al., 2014). On active or very young charcoal hearths (Hardy et al., 2016), the soil acidity in the substrate of the hearth is close to neutral.

CONCLUSION

Our comparative analysis of soils on charcoal hearth sites and surrounding forest areas in Litchfield County, CT, shows considerable legacy effects of historic charcoal production on soil stratigraphy and properties. The documented hearth remains are situated in slope positions, often show a multilayered stratigraphy resulting from multiple site usage, and have very thick topsoil sequences as compared with the surrounding forest soils. Therefore, the architecture of the charcoal hearths varies as compared with flat-land sites (Fig. 5a, b). The striking differences in stratigraphy and topsoil thickness documented for hearth and forest soils in our study affirm the relevance of a specific consideration of charcoal hearth sites in soil taxonomy (Fig. 5c).

The comparison of organic carbon concentrations suggests that the estimated PyOM accounts for about 30% of the total carbon on charcoal hearth sites (Fig. 6) and that the additional PyOM increases the natural soils' carbon concentration per unit mass by more than 40%. Together with the high thickness of the charcoal-rich layers on the hearth sites, these values clearly affirm the relevance of charcoal hearth remains as long-term carbon pools in ecosystems. Only small differences were observed for nitrogen concentrations and acidity of hearth site and forest soil profiles in our study (Fig. 6). This suggests that a chemical differentiation of SOM and PyOM in future research is crucial for better understanding the interactions between charcoal hearth topsoils and vegetation. Furthermore, the architecture and stratigraphy of our studied hearth sites imply effects on the movement of soil water, which shows the necessity of also characterizing soil physical properties in future studies of charcoal hearth sites.

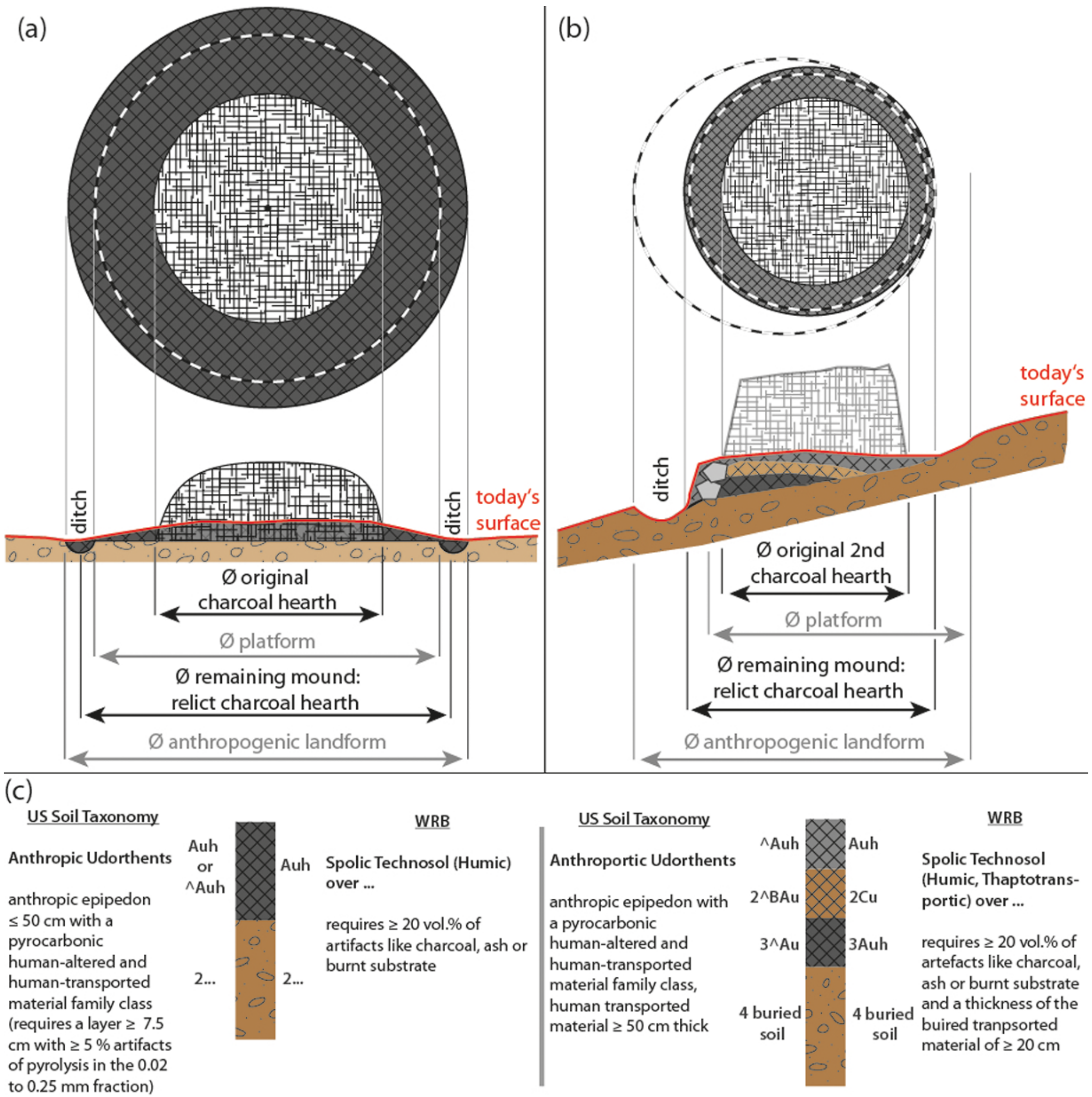

Fig. 5. (a) Simplified top view and cross section of a single used charcoal hearth in flat-land (modified from Raab et al. [2016]). (b) Simplified top view and cross-section of a multiple-used charcoal hearth on a slope. (c) Proposed classification of the charcoal hearth's soil according to USDA soil taxonomy and WRB.

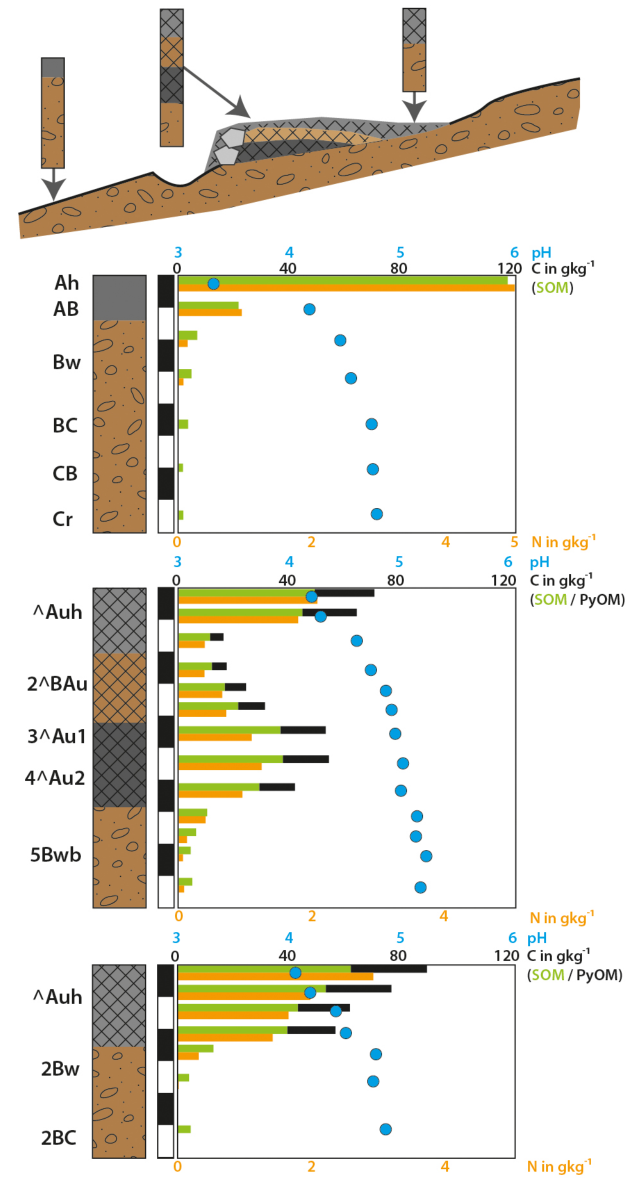

Fig. 6. Sketch showing soil chemistry of charcoal hearths vs. surrounding soils basing on the findings from charcoal hearth 16 (Fig. 3c, Table 1). Pyrogenic organic matter (PyOM) was estimated with 30% of total carbon. SOM, soil organic matter.

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SUPPLEMENTAL MATERIALS

The supplemental data contain the locations of investigated charcoal hearths and results from the carbon, nitrogen, and sulfur concentrations.

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