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Do small landforms have large effects? A review on the legacies of pre-industrial charcoal burning

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ABSTRACT

Relict charcoal hearths (RCHs) are small, anthropogenic landforms resulting from past charcoal burning and reaching significant land coverage in pre-industrial mining areas. We review three coupled legacies linked by RCH development: (i) a landscape-scale geomorphic effect, (ii) a unique soil fingerprint, and (iii) an evolving novel ecosystem. The history and technique of charcoal production are described to clarify legacy effects. Applying a recently presented morpho-genetic catalogue is useful for classified mapping of RCH findings. The RCH numbers and calculated RCH densities per study region vary greatly and impose uncertainties due to insufficient methods causing over- or underestimations. Areas with high RCH densities between 50 and 500 RCH/km^2 seem reasonable. Machine learning-based remote sensing techniques are promising approaches with which to better assess the full scale of charcoal burning legacies. RCH soil properties feature dark charcoal-rich technogenic substrate layers classified as Auh horizons according to the World Reference Base with significantly increased C contents. These Auh horizons can also exhibit specific physical and chemical properties, such as relatively low bulk density, high porosity, high plant available water content, low thermal conductivity and differences in cation exchange capacity or nutrient status. However, relevant studies are rare, and thus, the effects may differ by study region. Regarding vegetation, there seem to be four main effects: changes in forest structure, species composition, recruitment pattern and productivity. The number of studies on this issue is, however, also very limited. Even fewer studies have examined the soil fauna in RCHs; thus, the reported effects cannot be used to draw general conclusions. Notably, RCH research has made considerable progress in the last five years, especially in the Light Detection and Ranging-based mapping of these small landforms and identification of RCH-specific soil properties, but ecological legacies are not well understood; thus, more interdisciplinary and integrative studies are needed.

1. Introduction

Digital elevation models (DEMs) recorded by Light Detection and Ranging (LiDAR) are now available for large areas, providing an opportunity to map small landforms for the first time at high resolution and over larger areas (Tarolli et al., 2019). The majority of these small Earth surface structures are of anthropogenic origin, and their formation is often ancient. The newly visible microrelief can therefore reflect the imprints of centuries or millennia of past land uses. However, the human imprint of past cultures and historical land uses are often not the main foci of geomorphological, pedological and ecological research, although the relevance of land use legacies for ecosystem functioning and soil development is increasingly recognized and acknowledged (Foster et al., 2003; Wohl, 2015).

Among the anthropogenic structures identified in the new high-resolution DEMs, relict charcoal hearths (RCHs) are particularly widespread and abundant. RCHs are remains of past forest use and are mainly found in pre-industrial mining areas of Europe and North America. They

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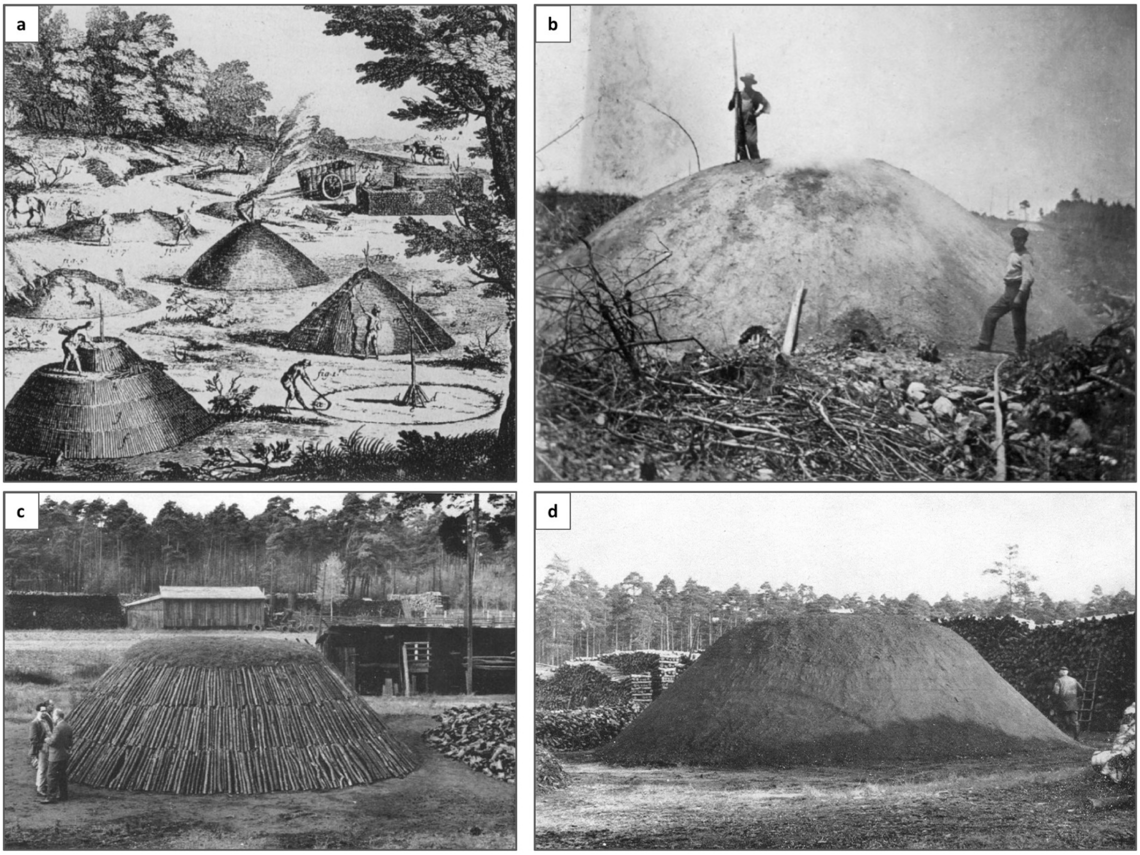

Fig. 1. Some historical images from charcoal hearths. Fig. 1a. Copperplate engraving Duhamel du Monceau (1761); modified. Fig. 1b. Charcoal hearth in Connecticut, USA, late 19th century (Source unknown). Fig. 1c. (Sorbisches Kulturarchiv am Sorbischen Institut in Bautzen, Nawka, 1966).

normally have a relative height of fewer than 50 cm on flat terrain and a horizontal dimension ranging from approximately 5–30 m. On slopes, height differences can increase to or even exceed one metre.

Despite their small spatial dimensions, RCHs can display significant land coverage due to their large number. RCHs are therefore a strongly underestimated element in many cultural landscapes even though they most likely play an important role in changes in terrain topography, soils, soil microbial communities, vegetation and their coupled water, carbon and nutrient cycles, calling for coordinated research. In this paper, we review three main coupled legacies linked by RCH development: (i) a landscape-scale geomorphic effect, (ii) a unique soil fingerprint, and (iii) an evolving novel ecosystem.

2. RCHs – a brief history and technical basics

2.1. History of charcoal burning

Charcoal making, the production of charcoal, is a historical form of forest use. In pre-industrial and early industrial times, charcoal was needed for various trades (e.g., mining and metallurgy), in crafts (e.g., blacksmithing) and for domestic use. The particularly high demand for charcoal was met above all by iron and steel works. Therefore, historical charcoal burning was often the basis for regional economic development.

In Germany, charcoal production was primarily practised in former nationally important mining centres of the low mountain ranges, such as the Black Forest, the Harz Mountains and the Upper Palatinate. However, numerous relicts of charcoal hearths in the North German Lowland also prove that charcoal was produced on a larger scale. Charcoal burning was largely abandoned in Germany in the mid-19th century, when charcoal was replaced by other energy sources, such as hard coal or lignite.

In addition, charcoal making was widespread in many other regions of Europe and in the northeastern United States. Charcoal production in the early Virginia and Massachusetts colonies of the later U.S. began in the 1600s (Baker, 1985). During much of the 19th century, the United States extensively used charcoal as a fuel for smelting and iron making in the eastern part of the country (Baker, 1985; Rolando, 1991; Straka, 2014; Straka, 2017) and for other metals such as silver, gold, or lead in the west (Straka, 2014); peak production was the mid-19th to early 20th century (Baker, 1985; Straka, 2014). Most production was in the eastern U.S.; thus, the numbers of furnaces and associated hearths are typically greatest today in the east (Straka, 2014). The development and widespread use of LiDAR technology in the U.S. has made finding hearths in present-day landscapes much easier and revealed their extensive but locally intensive spatial co-occurrence with the furnaces they supported (Johnson et al., 2021).

In many countries, charcoal is still produced in the traditional way, sometimes on a large scale, e.g., in Egypt, Brazil, Kenya, and Madagascar. This is often accompanied by drastic consequences for the environment. The most drastic impact is obviously deforestation (or on the landscape scale: forest degradation), but there are many more impacts on ecosystem services and functioning (Chidumayo and Gumbo, 2013; Codreanu-Windauer, 2019; Groenewoudt, 2007; Groenewoudt and Spek, 2016; Hirsch et al., 2020). Due to increased surface runoff, the hydrology of catchments may, for example, be adversely affected. However, these kinds of charcoal effects are hardly comparable to those of pre-industrial activities in Europe and North America and are not the focus of this paper.

Fig. 2. Some images from charcoal hearth construction and charring.
Fig. 2a. Architecture of a charcoal hearth. "Quandelschacht" is seen in the centre. The hearth is only partly covered to the right and left. Image taken in 2021 at the Stemberghaus, Harz Mts., Germany, © T. Raab. Fig. 2b. A charcoal hearth surrounded by a rim of charcoal left over from the last charring process. Image taken in 2015 in the Fichtelgebirge, Bavaria. Germany, © T. Raab. Fig. 2c. A charcoal hearth in operation. The wood logs are covered with soil. Aeriation is controlled by the collier standing beside the hearth using a wooden stick for pricking small holes in the hearth from which white smoke is released. Hearth location of the Kienstubbenverein Groß-Lindow, Brandenburg, Germany, 2019, © Bonhage. Fig. 2d. Harvesting of a charcoal hearth. After removal of the cover, charcoal fragments are taken out of the hearth. Hearth location of the Kienstubbenverein Groß-Lindow, Brandenburg, Germany, 2019, © Bonhage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Charcoal hearth types

Different types of charcoal hearths were used for charring wood (Figs. 1, 2, 5). Regarding their terminology, in the literature, there are several terms that can be very confusing, such as the synonymous usage of charcoal hearth, charcoal mounds and charcoal kiln. Although the last term is also used in the literature to describe an above-ground wood stack hearth, a kiln is actually a brick-built structure.

The oldest archaeologically detectable relicts are pit kilns (German term Grubenmeiler). Remains of pit kilns are rarely recognizable above ground and thus are discovered only in the course of archaeological excavations (Codreanu-Windauer, 2019; Groenewoudt, 2007; Groenewoudt and Spek, 2016; Hirsch et al., 2020). Because of their poor efficiency and yield, pit kilns were replaced by above-ground hearth types. From the Upper Palatinate (Bavaria, Germany), however, it is known that both types were occassionaly used at the same time (Götschmann, 1985; von Voith, 1841).

In the case of above-ground hearths, a distinction is made between angular charcoal hearths (Langmeiler) and circular upright hearths (Platzmeiler). For angular hearths, stem wood was cut into pieces of equal length and horizontally stacked. This type was common, for example, in Scandinavia and Austria (Hennius, 2019; Klemm et al., 2005) but also in the Görlitzer Heide (Saxony, Germany) (Koschke and Menzel, 2007). In contrast, for circular upright hearths, logs of the same length (approximately 1 m length) were needed.

2.3. Technical aspects of charcoal burning

Because of the various types of charcoal hearths, there are also a variety of landforms generated by charcoal production. However, to date, the majority of findings refer to former above-ground circular upright hearths. For this kind of hearth, flat, round surfaces, so-called hearth platforms, were constructed. The hearth platforms commonly had diameters of 8 to 12 m, but they also ranged between 4 and 30 m depending on the natural setting and contemporary regulations. In low mountain ranges, charcoal burners purposefully laid out small flat platforms on the slopes where the charcoal hearths could be built. The construction of these charcoal hearth platforms usually led to a significant change in the relief of the slope, and in many cases, conspicuous round or elliptical platforms can be found in the forests of the low mountains, which are characterized by rearrangements of soil or rocks. In contrast, in the lowlands, less effort was required to prepare the platforms. The site was merely levelled, and vegetation and larger rocks were removed. The hearth platforms are often surrounded by a ditch or a set of pits (e.g., Hirsch et al., 2020; Rutkiewicz et al., 2019; Rutkiewicz et al., 2017). In some regions, such ditches were mandatory for protection against forest fires (see, for example, the royal Prussian order regulating forest logging and charcoal burning under König Friedrich II (1779)). Elsewhere, ditching was intended to protect the pile site from flooding during rain events.

For the construction of the piles, dried wood was used, which was specially stacked in a hemispherical to conical shape (Fig. 2c). Then, the wood pile was covered with sod, moss, brushwood or a similar material.

Table 1
RCH findings reported in literature sorted by country.

Study author(s)	Country	Region	Size study area (km^2)	RCH number	RCH density (km^{-2})	RCH type[1]	Reference[2] Comments
Klemm et al. (2005)	Austria	Styria				3a	2
Deforce et al. (2013)	Belgium	Zoerselbos	1.5	49	33	2a, 2b	2
Hardy et al. (2016)	Belgium	Wallonia		208			2
Hardy (2017)	Belgium	Wallonia		400,000–450,000	Median 1.2 per ha	2b, 2c, 3b	Numbers are estimated
Hazell et al. (2017)	England	Barbon Park, Cumbria	0.7	34	48	3	2
Foard (2001)	England	Rockingham Forest			0.5		2
Fruchart (2014)	France	France	16.5	2000	121		1
Paradis-Greinouillet et al. (2014)	France	Mont Lozère		230			Field survey, no spatial data
Py-Saragaglia et al. (2017)	France	Pyrenees, Ariège		31	60		2
von Kortzfleisch (2008)	Germany	Harz		30,000	5–166		Numbers are estimated, Densities from different study areas
Ludemann (2003)	Germany	Black Forest (south)		2000	40		2
Ludemann (2010)	Germany, France	Black Forest, Vosges, Jura mountains		2800–10,000	150		2800 verified, 10,000 estimated
Raab A. et al. (2017)	Germany	Lower Lusatia, Brandenburg	109	5926	440	2b	2
Schmidt et al. (2016)	Germany	Hesse, Reinhardswald & Kellerwald Edersee		3934	1 RCH per 7.7 ha - 1 RCH per 4.3 ha		2
Schneider et al. (2020a)	Germany	Northeast Bavaria	10,700	>47,000	4.3	2a, 2b, 3b, 3c	2
Schneider et al. (2020a)	Germany	Brandenburg	29,500	>47,000	1.6	2a, 2b, (3b)	2
Tolksdorf et al. (2020)	Germany	Ore Mts.		348	40–81		2
Stöckmann (2006)	Germany	Müritz National Park		>1150			2
Stolz et al. (2012)	Germany	Kemel Heath, Rhenish Massif		40	0.11		2
Carrari et al. (2017a, 2017b)	Italy	Tuscany			5.5		2
Mastrolonardo et al. (2018)	Italy	Tuscany	0.16	35	200–300		2
Risbøl et al. (2013)	Norway	near Oslo		205			2
Rutkiewicz et al. (2017)	Poland	River Czarna Valley, Central Poland		11,500	95	2b	2
Rutkiewicz et al. (2019)	Poland	Mala Panew River, Southern Poland			184		2
Eriksson and Glav Lundin (2021)	Sweden	Åkers mining district			6.6		2
Pèlachs et al. (2009)	Spain	Vallferrera	9.2	924	100		2
Carter (2019)	USA	Pennsylvania	74	758			2
Suh et al. (2021)	USA	New England	493	6245	13		2

[1] RCH types according to Hirsch et al. (2020) are (see also Fig. 4):
1a – negative relief feature, pit charcoal production.
2a – RCH on flatland, positive relief feature, mound-like RCH.
2b – RCH on flatland, positive relief feature, circular RCH with ditch.
2c – RCH on flatland, positive relief feature, circular RCH surrounded by a ridge.
3a – RCH on slope, positive relief feature, angular RCH.
3b – RCH on slope, positive relief feature, with levelled surface.
3c – RCH on slope, positive relief feature, platform with ridge.
[2] Data source is (1) Rutkiewicz et al. (2017), and (2) own research from cited publication.

To seal the charcoal pile to be as airtight as possible, this covering was followed by a final layer for which RCH substrate was usually used (Fig. 2d). This is a heterogeneous substrate - a mixture of minerogenic material and organic material - from charring at a previous charcoal production site. Thus, the RCH substrate was thermally modified and enriched with charcoal fragments (fine dust to pieces). Depending on the size of the charcoal pile, the amount, type and moisture of the wood that it contained, and the weather conditions, charring took approximately 10 to 14 days.

Numerous historical sources and books provide information about the technical process of charcoaling (e.g., Cramer, 1798; Duhamel du Monceau, 1761; Krünitz, 1773–1858; von Berg, 1860). The charcoal itself is always produced according to the same principle of pyrolysis (= dry distillation). When wood is smouldered with oxygen largely excluded, charcoal is produced by thermo-chemical conversion processes. As the wood smoulders, oxygen is consumed, but the air supply from outside is obstructed by the cover. The air supply must be controlled so that the wood only smoulders and does not burn to ash (Fig. 2c). During the charring process, temperatures of approx. 200 to 380 °C, and in some places up to 500 °C, are reached. These high temperatures result in thermal decomposition of the wood (Meyer, 1997).

The raw wood material consists mainly of highly polymeric carbon compounds: 40–50 % cellulose, 20 % hemicellulose, 20–30 % lignin, and other substances such as tannins and dyes, resins, salts, protein, and acetyl (von Kortzfleisch, 2008). In the hearth, after ignition under the exclusion of air, the decomposition of the wood begins at a temperature of 100 °C (= decomposition phase). In the pyrolysis phase (200–350 °C) and in the charring phase (above 350 °C), solid, liquid and gaseous products are formed: charcoal, wood vinegar, wood tar and wood gas. While the volatile components burn, evaporate or vapourize, almost

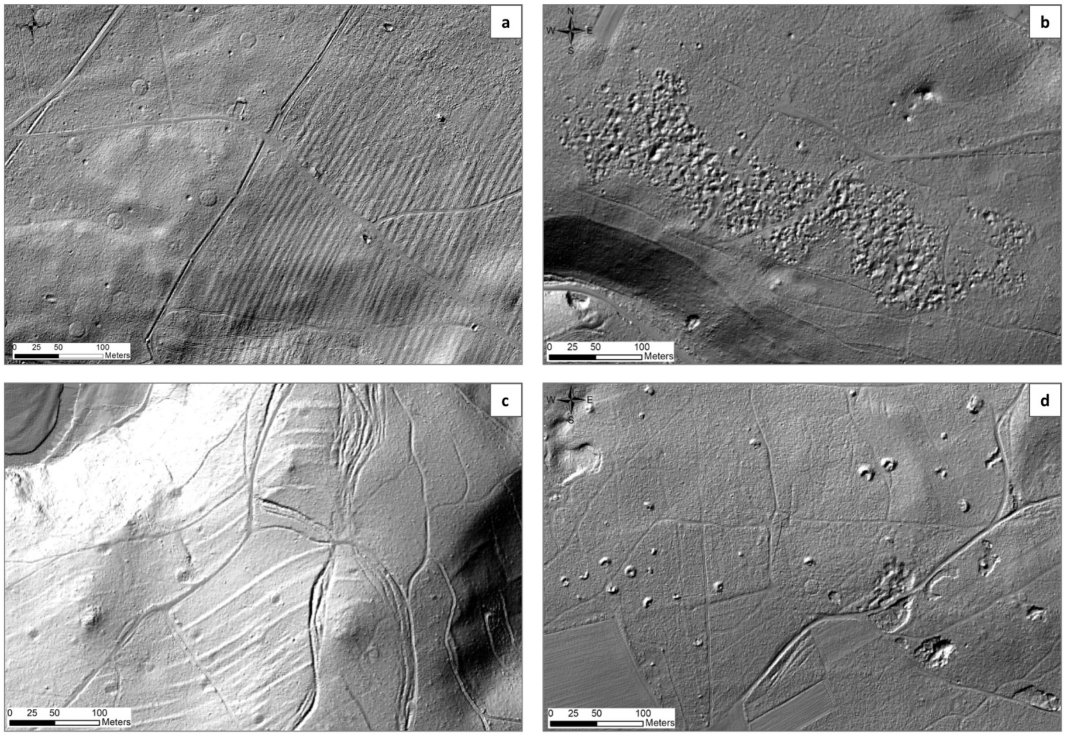

Fig. 3. Association of landforms resulting from historic land use including RCHs.
Fig. 3a. Relict charcoal hearths (RCHs) can be seen in the northwestern part, whereas ridge and furrow systems are found in the southeastern half. Tauer forest north of Cottbus, Brandenburg, Germany. Fig. 3b. A field of mining shafts near Theuern-Wolfsbach, Upper Palatinate, Bavaria, Germany. Two circular RCHs can be seen at the eastern edge of the mining area, one in the north and one in the south. Fig. 3c. RCHs, hollow ways, and lynchets near Tännesberg, Upper Palatinate, Bavaria, Germany. Fig. 3d. A group of approximately one dozen mining shafts surrounded by typical rims near Amberg-Haidweiher, Upper Palatinate, Bavaria, Germany. In the centre of the image, an isolated circular RCH with a surrounding ditch can be seen. Outcrops in the southeastern sector are not classified.

pure carbon and some mineral ash remain (Meyer, 1997). The by-product tar is formed only when coniferous wood is carbonized.

3. RCH – the geomorphological legacy

3.1. RCH – one aspect of human-induced landscape change

The question of how humans have modified Earth's surface during the Holocene has been examined for decades. For example, the effects of farming-induced soil erosion on slopes initiated in the early Neolithic (e.g., Dotterweich, 2013; Vanwalleghem et al., 2017) or the changes in alluvial systems caused by floodplain sedimentation, river constructions, etc. (e.g., Gębica et al., 2013; Howard et al., 2016; James, 2013; Macklin et al., 2006; Macklin et al., 2014; Malik et al., 2015), have been studied extensively. Recently, the invention of the term “Anthropocene” – although not (yet) a geological one – puts a new perspective on these geomorphological processes and landforms, demonstrating “(…) how extensive and significant human impacts on geomorphology have been” (Goudie and Viles, 2016: 1). However, the picture of anthropogenic geomorphology is still blurred and incomplete (Brown et al., 2017) because there are hidden, partly forgotten and understudied geomorphological relicts of past land use in forests of (mainly) industrialized countries. Although rather old, ancient woodlands at the mid-latitudes have seen different land uses throughout their history, such as ploughing, grazing or charcoal burning, and numerous studies on vegetation reconstruction describe a diverse history of human-induced deforestation and afforestation as well as of changing tree species composition and management regimes in the last millennia (e.g., Groenewoudt and Spek, 2016). Until the 19th century, forest coverage in Central Europe declined significantly, but since then, woodlands have recovered mainly because of reduced timber consumption and charcoal production after fossil fuels replaced the traditional energy resources wood and charcoal (see, e.g., Kaplan et al., 2017). This land use change had an important effect by helping to preserve the geomorphological legacy (Wistuba et al., 2018). The developing tree vegetation sheltered ancient landforms, whereas on adjacent farmland, >100 years of intense ploughing with heavy machinery destroyed the pre-industrial Earth surface nearly completely, resulting in a smoothed relief. Johnson and Ouimet (2018) presented an observational and theoretical framework for interpreting the landscape palimpsest through airborne LiDAR. They emphasize the need to deal with the geomorphological legacies of former land uses that have been left behind as part of the cultural landscape.

The large-scale geomorphological legacy of RCHs, as one aspect of historical land use, is still not completely known, although several case studies describe principles about their architecture, construction history and spatial distribution (Table 1, Fig. 2). Especially in regard to quantification, such as RCH number or density, only a few studies provide accurate data or encompass larger areas; e.g., for the forest area Tauer in South Brandenburg, Germany, a characteristic thickness of 0.18 m ± 0.03 m for RCH substrates and an RCH soil coverage of 1.5 % have been determined (Bonhage et al., 2020b; Schneider et al., 2022). However, the results of such case studies are not directly transferable to other regions without an understanding of the interdependencies between natural conditions and RCH distribution and stratigraphy, e.g., which sites were chosen for hearth construction, how often these sites were used for operating a hearth, and how well RCHs have been preserved over centuries, depending on substrate and later forest use, etc. Therefore, more regions must be thoroughly investigated, and more spatial data should be acquired in an integrative approach. Only such a comprehensive database will provide universal results on the geomorphology of RCH landscapes and thus can be used to assess their importance for soils and biota. However, some facts and example data can be gathered to set a starting point and basis for further research (see following sections).

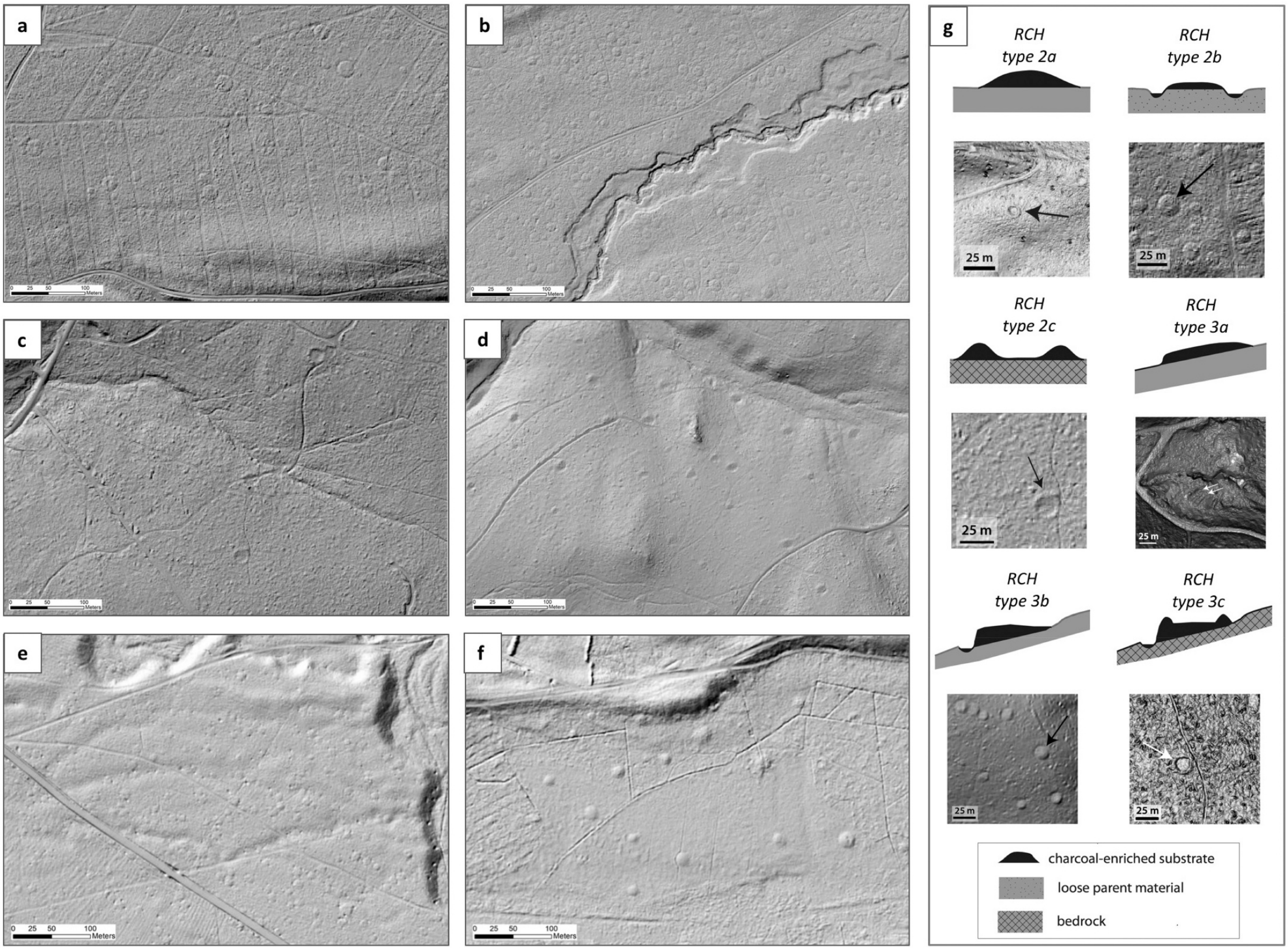

Fig. 4. Shaded relief maps from LiDAR-based digital elevation models (DEMs) (600 m * 400 m) showing groups of RCHs.
Fig. 4a. Circular RCH surrounded by a ditch with a characteristic medium spatial density (near Wernberg-Köblitz, Germany). Fig. 4b. Circular RCH surrounded by a ditch with an exceptionally high spatial density (southeastern Nuremberg, Germany). Fig. 4c. Circular RCH surrounded by a ridge with a characteristic low spatial density (near Warmensteinach, Germany). Fig. 4d. RCH slope platforms with levelled surfaces with a characteristic medium spatial density (near Tännesberg, Germany). Fig. 4e. RCH with pits near Brusiek village with a high spatial density, close to Mala Panew River, Poland. Fig. 4f. Elevated RCH with a medium spatial density near Tworog, valley of the Mala Panew River catchment, Poland. Fig. 4g. Most common RCH types and their landform legacies (adapted from Hirsch et al., 2020).

3.2. RCH – distribution and morphological types

RCHs are found in several European countries and the U.S., especially in Germany, Poland, Italy, France, Spain, England, Norway and Sweden, as well as in the New England states (Table 1). The RCH numbers published in the studies vary greatly for several reasons. First, the different sizes of study areas cause different total numbers; i.e., the RCH number is usually higher in larger areas. However, this does not necessarily mean a higher RCH density. Even in small study areas, there can be relatively many RCHs, or in large areas, RCHs may not be evenly distributed but form spatial clusters, as reported, for example, in Raab et al. (2019) and Schneider et al. (2022). Second, not all RCHs were mapped systematically, with the research instead partly dedicated to soil or vegetation topics, where only some RCHs were selected as examples. Third, the surveys did not follow a uniform methodology. In particular, the quality of the LiDAR data and other parameters, especially relief and vegetation type, density and height, influence the search results and can lead to significant underestimation or misinterpretation. For example, Bonhage et al. (2020b) have shown that RCHs identified by manual/visual evaluation represent only approximately 42 % of the RCHs verified on site and by groundtruthing. Ultimately, numbers on the distribution, frequency and density of RCHs must be assessed against the background of the respective situation and methodology.

Despite these constraints, quite accurate specifications for the density and distribution of RCHs can be made for some areas where precise information has been gathered through intense mapping. For example, Raab et al. (2019) and Schneider et al. (2022) were able to determine an average density of 38 RCHs per km^2 for the Tauersche Forst in Niederlausitz, South Brandenburg, and maximum densities of >200 sites per km^2. Rutkiewicz et al. (2019) calculated a density of 184 RCHs per km^2 for a forest area in southern Poland. Measurements or at least approximate estimates of the morphology and the thicknesses or volumes of the charcoal-rich RCH layer are important information for calculating additional soil organic matter (SOM) and answering further questions, e.g., related to hydrology or ecology (Bonhage et al., 2020a).

Hirsch et al. (2020) presented a catalogue of the most common forms of RCHs based on a morphological-genetic classification of RCHs in Central Europe (Fig. 4g). Shaded relief map (SRM) examples can be found for all seven RCH types. As research from the U.S. shows, the classification can also be applied to the RCHs in New England.

With regard to the types of RCHs that have been identified by LiDAR or SRM mapping, there is a predominance of round and slightly elliptical

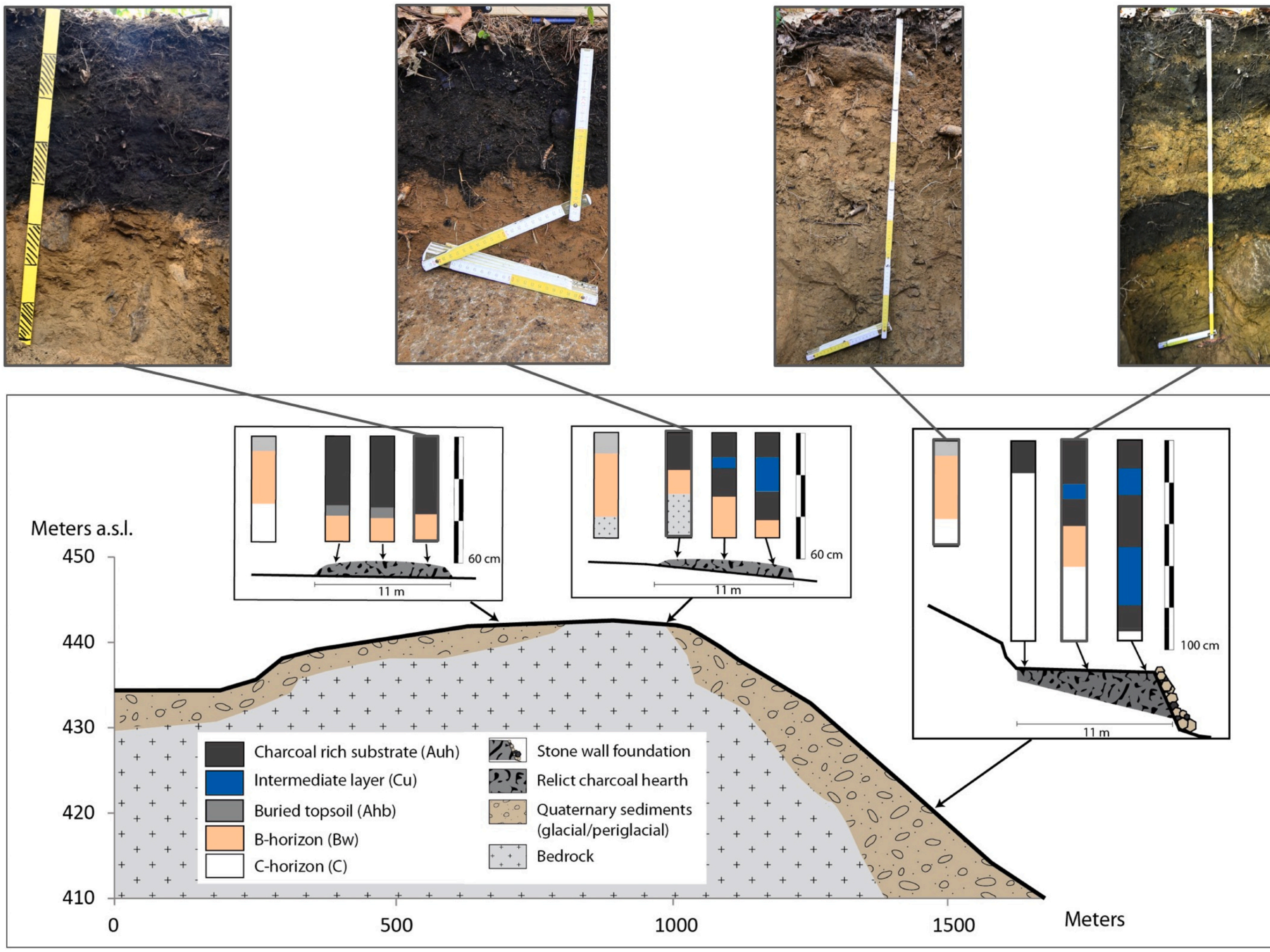

Fig. 5. RCH morphology, architecture and soil stratigraphy on a *catena* in West Connecticut (draft by A. Bonhage).

shapes, which are the legacy of the typical above-ground circular upright hearths (see Figs. 2, 3, 4). Despite the considerable variety of historically known charcoal hearth types (e.g., Hennius, 2019), rectangular or trapezoidal shapes play only a minor or regionally significant role. Circular RCHs are found both in the lowlands (Hardy and Dufey, 2015; Raab et al., 2019; Raab et al., 2015; Rutkiewicz et al., 2019; Schirren, 2007) and in the low mountain ranges (among others Ludemann, 2010; Ludemann et al., 2017; Swieder, 2019), and they are common in both Europe and the USA.

In some areas, RCHs are quite uniform or evenly distributed over the area, e.g., on the slopes in Connecticut (Bonhage et al., 2020b; Johnson and Ouimet, 2014) or in Bavaria (Fig. 4d). RCHs can also be associated with other forms of historical land use, including old field terraces, ridges and furrows, hollow ways and paths (Fig. 3a, c) or mining relicts such as mine pits (Fig. 3b, d).

3.3. RCH identification – from field surveys to machine learning-based automated mapping

Before the widespread availability of high-resolution LiDAR data, RCHs were field-mapped during ground surveys on a comparably small scale (e.g., Bond, 2007; Bonhôte et al., 2002; Ludemann, 2003; von Kortzfleisch, 2008; Young et al., 1996). The morphological characteristics of RCH sites described in Section 3.2 result in microrelief features detectable in the field by the trained human eye. On flatland, the circular elevations surrounded by a shallow ditch or multiple pits usually form a good enough contrast to the surrounding terrain to make them detectable; however, understorey vegetation and disturbances by forestry activities sometime obstruct this view (Raab et al., 2015; Risbøl et al., 2013). Sites on slopes predominantly form an excellent relief contrast, as the artificially created platforms are easily visible as breaks in the slope. These small-scale negative-positive elevation contrasts make RCHs ideal candidates for digital mapping techniques based on high-resolution LiDAR-derived DEMs, much like, e.g., burial mounds in the field of archaeology.

The earliest approaches involved mapping sites manually using a variety of DEM-derived relief visualizations, such as local relief models and hillshade maps (e.g., Deforce et al., 2013; Hesse, 2010; Raab et al., 2015; Risbøl et al., 2013). With increasing LiDAR data coverage, mapping efforts have expanded to ever larger areas, culminating in several studies that cover hundreds to thousands of square kilometres, resulting in databases of ten to hundreds of thousand RCH sites (Rutkiewicz et al., 2019; Schneider et al., 2020a). It is clear now that RCHs are a widespread feature of central European and northeastern U.S. forests, so widespread that the task of manually mapping them digitally becomes inefficient. The first semi-automated mapping approach on a larger scale reported by Schneider et al. (2015) used a template matching approach in a GIS environment. Withanara et al. (2018) applied geographic object-based image analysis (GEOBIA) for sloped areas in Connecticut to extract RCH features from DEMs. In recent years, machine learning-based object detection has become increasingly popular and efficient for geoarchaeological and archaeological research (Opitz and

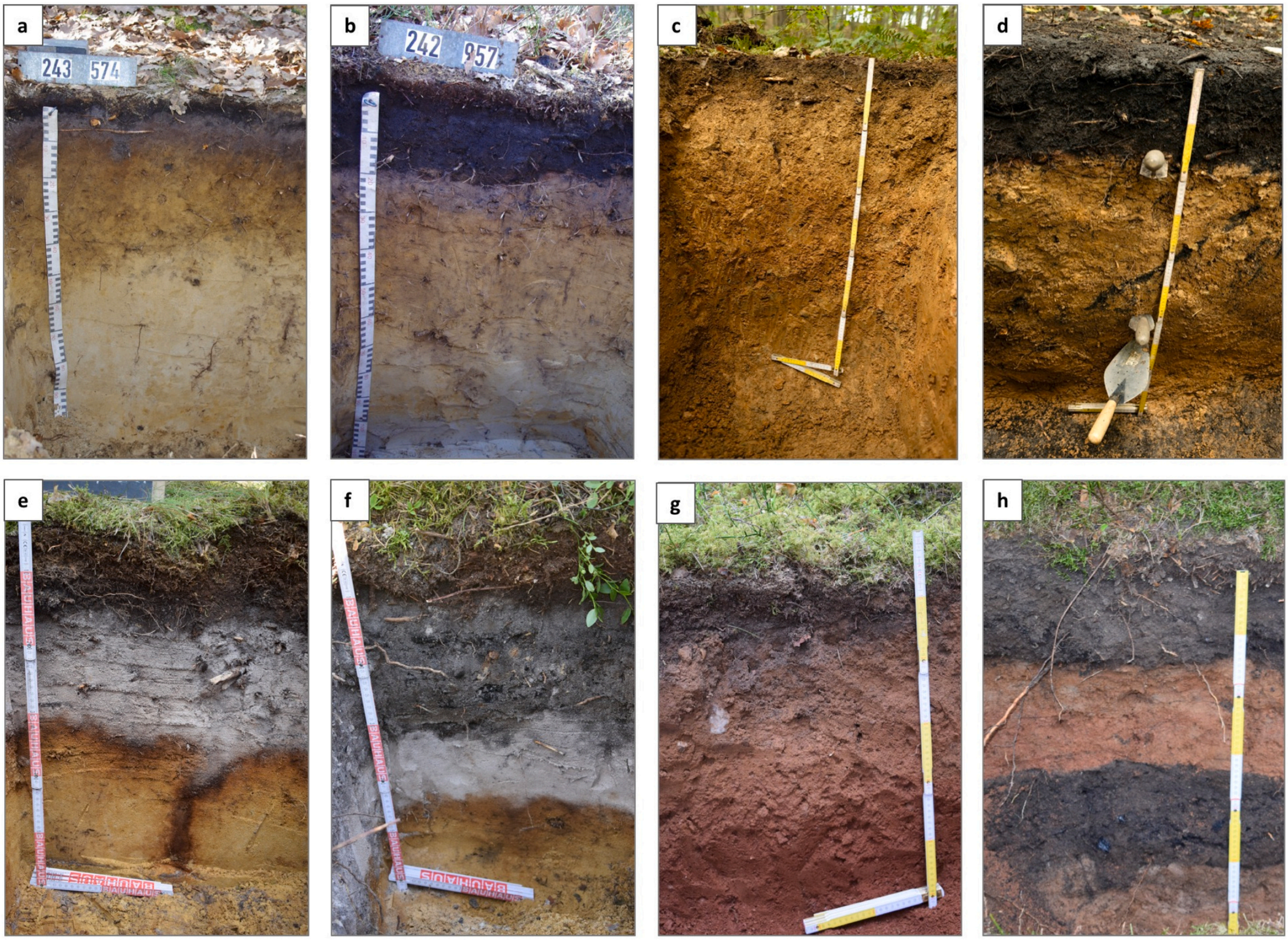

Fig. 6. Soil profiles. Examples from different regions. Fig. 6a: Cambic Arenosol in the direct vicinity of the RCH soil seen in Fig. 6b. Tauerscher Forst, Kleinsee, north of Peitz, South Brandenburg, Germany. This soil with a distinct, c. 40-cm-thick Bw horizon is typically found on sand-rich Quaternary deposits in the North German Lowland and exhibits weak podzolization in the first centimetres. Fig. 6b: RCH soil of the same area as in Fig. 6a. On top of the black, 20-cm-thick Auh layer, L and O layers have formed under the sessile oak (*Quercus petraea* (Matt.) Liebl.)-dominated forest with minor Scots pine (*Pinus sylvestris* L.). At 20–25 cm, the weakly podzolized, buried 2 Auh can be seen, followed by the Bw horizon. Fig. 6c: Luvisol in the direct vicinity of the RCH soil seen in Fig. 6d. Pennsylvania, USA. Fig. 6d: RCH soil of the same area as in Fig. 6c. Fig. 6e: Podzol in the direct vicinity of the RCH soil seen in Fig. 6f. Tannenwald, north of Peitz, South Brandenburg, Germany. This soil with a striking, ash-grey E horizon followed by the orange to red Bhs horizon is typically found on sand-rich and quartz-dominated Quaternary deposits in the North German Lowland. In comparison to the cambic Arenosol from Fig. 6a, this soil is more acidic. Fig. 6f: RCH soil of the same area as in Fig. 6e. Dark Auh horizon with charcoal fragments over the buried 2 E horizon. Fig. 6g: Reference soil profile in the direct vicinity of the RCH in Fig. 6h. Fig. 6h: Two-layered RCH soil profile from Weiherhammer, NE Bavaria, Germany. Orange to reddish colours of the B and C horizons derive from the iron-rich sandstone comprising the soil's parent material. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Herrmann, 2018). Thereby, datasets with manually digitized and labelled sites are used to train convoluted neural network (CNN)-based object detectors for site locations and segmentation (e.g., Bonhage et al., 2021; Kazimi et al., 2019; Trier et al., 2021; Verschoof-van der Vaart and Lambers, 2019; Verschoof-van der Vaart et al., 2020).

Although the reported mapping accuracies of recent studies are impressive, there is an inherent error associated with site detection on DEMs. It has been shown that there can be large disparities between field- and DEM-based manually mapped sites for an area. For example, Bonhage et al. (2021) reported that >50 % of the actual RCH sites for an area in the North German lowlands were not detected by humans. This error associated with LiDAR point densities and human factors is then of course transferred to CNN-based models via training data. Nonetheless, the major advantage of machine learning-assisted mapping is the ability to scan large areas relatively quickly and systematically (Verschoof-van der Vaart et al., 2020), with the potential for the complete workflow to be realized using freely available open source software and LiDAR data (Carter, 2019). Current advances in machine learning-based remote sensing techniques therefore greatly facilitate the detection of the full-scale legacy effect that historic charcoal burning has on today's soil landscapes, and it can be expected that complete coverage for counties and states will be achieved soon.

4. RCHs – the pedological legacy

As soils at the mid-latitudes are relatively shallow and the average solum depth is often less than one metre, minor relief modifications can significantly change pedosphere properties and soil distribution. This effect is well known and examined in agricultural areas where soil erosion processes are not only visible but directly measurable and can have dramatic consequences for fertility as well as for mass and matter fluxes. Historical relief modification and subsequent changes in the soil landscape in modern woodlands are rarely studied, with the main focus instead on distinct landforms such as gullies or colluvial sediments (e.g.,

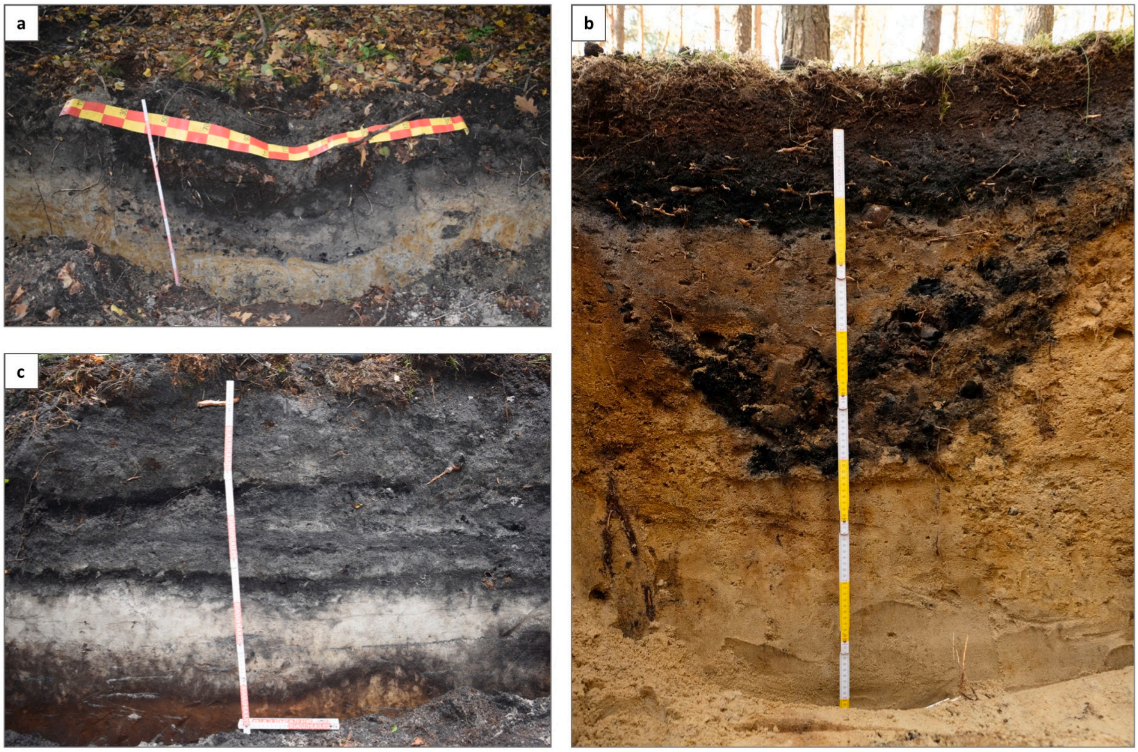

Fig. 7. Soil profiles. Examples from different regions. Fig. 7a: Soil profile in the pit of a flatland RCH in Tarnowsky Gory, Silesia, Poland. The reference soil is a Stagnosol. Fig. 7b: Soil profile in the ditch of a flatland RCH at Tauerscher Forst, Kleinsee, north of Peitz, South Brandenburg, Germany. Reference soil is the same as in Fig. 6a. Fig. 7c: RCH on Podzol in the Mala Panew River catchment, Silesia, Poland.

Dreibrodt et al., 2009; Reiß et al., 2009).

The existence of RCHs in woodlands has been known since their first appearance; however, research on RCH soils is rare. Recently, RCH soils have been investigated in several regions, e.g., Connecticut (Hirsch et al., 2018a), Italy (Carrari et al., 2018; Criscuoli et al., 2016; Mastrolonardo et al., 2018), Belgium (Hardy et al., 2016), and Germany (Hirsch et al., 2018b; Schneider et al., 2018; Schneider et al., 2019).

Table 2

Overview on soil physical properties of RCH soils observed in available studies. If soil properties were determined for more than one depth, only values for the topmost sampling depth are reported. Numbers in parentheses are reference soil values.

Study	Location	Soil texture	RCH age	Hydraulic conductivity [cm h^{-1}]	Bulk density [g cm^{-3}]	Porosity [%]	Available water content [%]
Borchard et al. (2014)	Siegerland, Eifel; Germany		>60 years		0.61 ± 0.08 (0.88 ± 0.08)		
Criscuoli et al. (2014)	Italy, eastern alps	Sandy loam	16th–19th century		0.6 ± 0.08 (0.87 ± 0.12)		
Donovan et al. (2021)	USA, Connecticut	Sandy loam	18th–20th century		0.78 ± 0.13 (0.86 ± 0.12)		
Dupin et al. (2019)	Eastern France	Clay loam	160 + −30 years				
Faghih et al. (2018)	Northern Iran		>120 years	8.70 ± 0.98 (5.73 ± 0.93)	1.00 ± 0.01 (1.14 ± 0.05)		22.34 ± 0.98 (16.66 ± 0.33) (pF 2.5–4.2)
Kerré et al. (2017a, 2017b)	Belgium		>150 years				31 (28) (pF 1.8–4.2)
Mikan and Abrams (1995)	USA, Pennsylvania	Sandy loam	18th–19th century		0.65 ± 0.03 (0.96 ± 0.03)	59.7 ± 2.3 (46.6 ± 2.0)	
Oguntunde et al. (2008)	Ghana	Loamy sand	Recent	87.9 % higher for RCH	1.3 ± 0.1 (1.4 ± 0.1)	50.6 ± 4.5 (45.7 ± 4.6)	
Schneider et al. (2018)	Brandenburg, Germany	Sand	17th–18th century		1.1 - 1.4 (1.2 - 1.5)		
Schneider et al. (2020b)	Brandenburg, Germany	Sand	17th–18th century	Higher and more variable in RCH substrate	1.17 ± 0.16 (1.36 ± 0.12)	39.8 ± 5.2 (36.8 ± 6.7)	5.99 ± 2.9 (9.1 ± 5.3) (pF 2.5–4.2)
Zanutel et al. (2021)	Belgium	Silt loam, loam, sandy loam	19th century	No significant effects on saturated hydraulic conductivity	Decreasing with increasing charcoal content	No significant effects	Increasing with increasing charcoal-C content

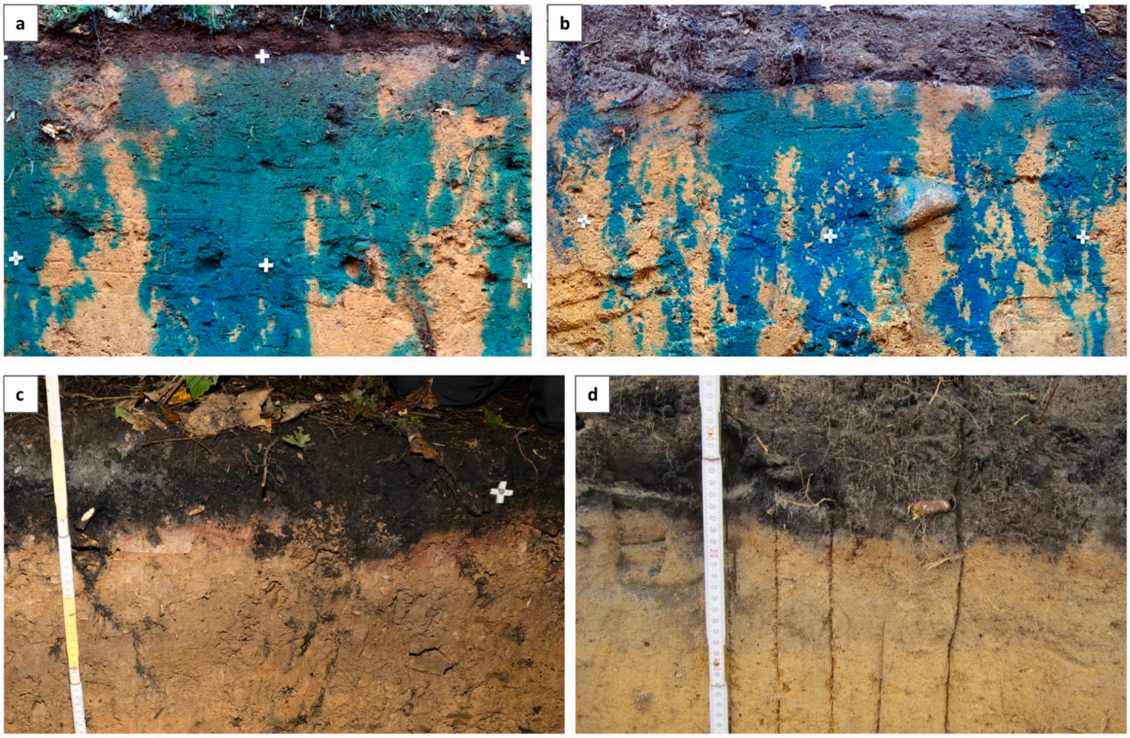

Fig. 8. Effects on physical soil properties. Fig. 8a, b: Infiltration patterns from a dye tracer experiment (Schneider et al., 2018) at a RCH near Jänschwalde in South Brandenburg, Germany (a: Infiltration patterns in a reference soil profile, b: strong preferential flow in technogenic RCH substrate). Fig. 8c. Heating-caused effect of charcoal burning on the buried soil and the formation of reddish hematite by dehydroxylation of goethite. Soil profile from Central Pennsylvania, USA. Fig. 8d. Heating-caused effect of charcoal burning on the buried soil and the formation of reddish hematite by dehydroxylation of goethite. Soil profile from Jänschwalde, Germany.

4.1. RCHs – stratigraphy and soil morphology

Several studies have shown that RCH soils have characteristic stratigraphies and properties. The most distinct features are charcoal-rich technogenic substrate layers formed from charcoal fragments remaining at the site after harvesting the hearths and from residues of the hearth sealing material (Fig. 6). While RCHs in flat terrain characteristically feature a single 20- to 40-cm-thick layer of this material, RCHs in sloped terrain often have multiple technogenic layers separated by intermediate mineral colluvial substrate layers, all with varying thicknesses depending on the position in the platform (Figs. 5, 6h).

The RCH substrate layers are considerably enriched with charcoal, resulting in higher C contents (Hardy et al., 2016; Hirsch et al., 2018a; Hirsch et al., 2018b; Mastrolonardo et al., 2018) and a distinct dark colour. According to the World Reference Base for Soil Resources (IUSS Working Group World Reference Base [WRB], 2014), these RCH layers are classified as Auh horizons, and the soils are therefore classified as Spolic Technosols (Hirsch et al., 2018a; Hirsch et al., 2018b). The buried topsoil horizons below the RCHs are modified to varying degrees, again mainly depending on the type and terrain position of the sites. For sites in flat terrain, both truncation of the underlying soils (Hardy, 2017) and almost complete preservation of the unaffected forest soils below the technogenic layers (Hirsch et al., 2018b) have been observed. These variations are related to regionally differing modes of site preparation associated with the properties of the underlying soils and sediments.

Working in Connecticut, Raab et al. (2016) noted that hearth construction resulted in a distinct, relief-dependent soil morphology. As in other low mountain ranges, RCHs on slopes in New England are usually located on more or less horizontal platforms that have been built to enable the construction of wood stacks. Due to the downslope rearrangement of soil material caused by platform construction, the profiles on the lower slope are usually thicker and often multi-layered (Fig. 5). At some RCHs in West Connecticut, downslope rims are reinforced with large boulders that can be seen at the basis of soil profiles (Bonhage et al., 2020b; Raab et al., 2016; Fig. 5). This multi-layered nature is particularly discernible in the case of parent materials that can be easily distinguished in colour from the dark pile substrates. Ideally, multi-layered RCH soils show sequences of dark, charcoal-rich Auh horizons interrupted by lighter charcoal-free or charcoal-poor horizons consisting mainly of displaced B or C solum. Thus, in the longitudinal section of the RCH, a characteristic microcatena is noticeable with Auh/B or Ah/C profiles at the upslope end and Auh/2B/3Auh/4Auhb profiles at the downslope edge. In relief situations with slopes of $<2^\circ$ degrees, typical of lowlands, the profiles are usually not stratified and have a uniform sequence of Auh/2Auhb or Auh/2Bb horizons. Often, these lowland RCHs then show a slight increase in Auh thickness towards the centre of the RCH.

4.2. RCHs – physical soil properties (including soil hydrology)

In addition to their dark colour, the most prominent characteristics of technogenic RCH deposits are their low bulk density and high porosity. Most studies of RCH soils report a clearly reduced bulk density in the technogenic substrate layers (Table 2), but detailed analyses of pore space have been carried out for only a few sites. For RCHs on sandy substrates with a single technogenic substrate layer, it has been shown that the low bulk density is mainly a consequence of high volumes of coarse pores and of the high intraporosity of large charcoal fragments, while the volumes of medium pores are not higher in RCH substrates than in surrounding forest topsoils (Schneider et al., 2018). Similar effects on pore size distribution can be assumed for other sites with high contents of large (>2 mm) charcoal fragments. In contrast, increased mesoporosity, but no significant effects on micro- and macroporosity, were found for sites on loamy agricultural soils in Wallonia (Zanutel

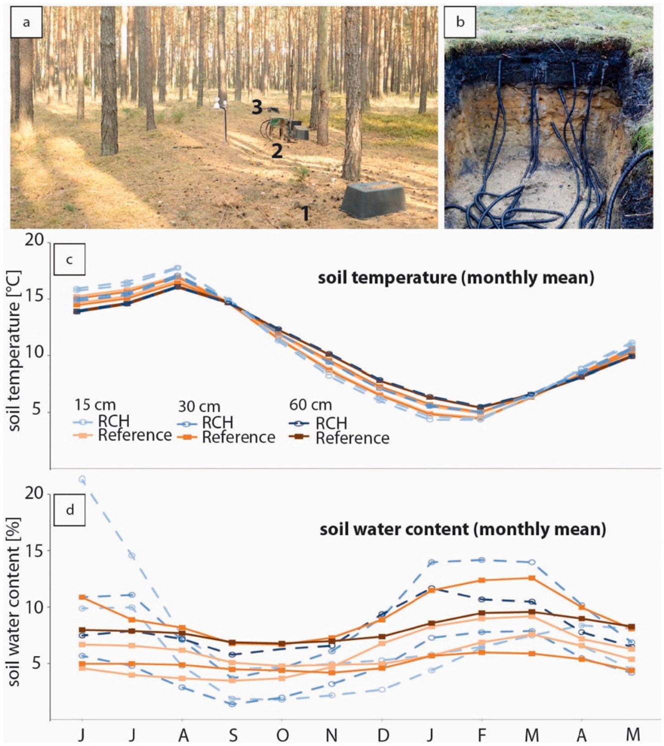

Fig. 9. Soil moisture and temperature monitoring for a RCH at Tauerscher Forst, South Brandenburg, Germany (Schneider et al., 2020b). Fig. 9a. Monitoring transect with location of instrumented profiles outside of the RCH (1), in the RCH ditch (2) and on the RCH platform (3). Fig. 9b. Installation of sensors for measurement of soil water contents, matric potentials and soil temperature in the RCH platform profile. Fig. 9c. Soil temperature (monthly mean values) for the RCH and reference soil profile from June 2018 to May 2019. Fig. 9d. Soil water contents (monthly mean values) for the RCH and reference soil profile from June 2018 to May 2019.

et al., 2021). The bulk density of buried topsoil horizons can be increased compared with that of surrounding topsoils, presumably as a result of mechanical compaction during site preparation and hearth operation (Schneider et al., 2018; Schneider et al., 2019).

The characteristic porosity of the RCH technogenic substrate affects water retention, water infiltration patterns and rates and heat transfer in RCH soils. Related to the high porosity and heterogeneity of the technogenic substrate, water infiltration rates are generally increased compared with those of unaffected forest soils. Higher saturated hydraulic conductivity of RCH soils has been observed for sandy soils in Germany (Schneider et al., 2018; Schneider et al., 2019), for RCHs on loamy sand in Ghana (Oguntunde et al., 2008) and for RCHs in Iran (Faghih et al., 2018). Zanutel et al. (2021) found no significant effects on saturated hydraulic conductivity for RCHs in Belgium but found pF-dependent effects on hydraulic conductivity curves for specific soil types. Borchard et al. (2014) determined a higher maximum water-holding capacity for RCH soils from Western Germany than for surrounding soils; however, they did not characterize the pore size distribution or plant water availability. Generally, high plant available water contents (AWCs) have frequently been assumed to be a main effect of charcoal addition to soils, mainly based on the observation of low bulk density and associated high porosity (e.g., Oguntunde et al., 2008). However, because the high porosity of RCH substrates can in large part be due to high volumes of coarse pores, it does not necessarily imply increased soil water retention and AWCs, and the effects differ depending on the regional parent material and land use. A higher AWC for RCH soils was found for loamy RCH soils on fertilized agricultural land in Belgium (Kerré et al., 2017a; Zanutel et al., 2021) and for RCH soils in northern Iran (Faghih et al., 2018). For RCHs in sandy forest soils in Germany, a lower AWC was observed within the Auh horizons, but the root zone AWC was still slightly increased at RCH sites due to the high thickness of the topsoil horizons (Schneider et al., 2018; Schneider et al., 2020b). Monitoring of soil water contents and matric potentials for sites in the forest area of Tauer (Fig. 10) shows that the characteristic porosity results in high water contents in RCH soils during wet periods, when water is infiltrating through and retained in large pores, but also in a more rapid drying and lower water contents of RCH soils during dry periods (Schneider et al., 2020b). For the same sites, it could also be

Table 3
Overview of studies discussing RCH soil chemical properties. Acknowledged where studies that list element concentrations in tables or appendixes. Properties where averaged whenever necessary. For brevity, if multiple sites from different location where discussed, then only the first one listed is included here. Numbers in parentheses are reference soil values.

Study	Location	Depth	pH	TOC	TN	BC	CEC
		[cm]		g kg^{-1}			cmol kg^{-1}
Burgeon et al. (2021)	Belgium	0–30	7.0 (7.1)	26.0 (14.0)	23.0 (14.0)		14.0 (12.0)
Hardy et al. (2016)	Belgium	0–25	5.0 (3.8)	41.1 (42.9)			9.6 (13.3)
Hardy (2017)	Belgium	0–25	5.7 (5.8)	34.5 (17.9)	2.4 (1.8)	13.5 (0.9)	16.6 (10.7)
Hardy (2017)	Belgium (Forest sites)	0–30		106.1 (50.4)		82.3 (n.a.)	
Hardy (2017)	Belgium (Cropland sites)	0–25		35.6 (17.5)		13.9 (n.a.)	
Hardy et al. (2019)	Belgium (Forest sites)	0–59	3.4 (3.1)	85.7 (72.5)		53.8 (1.2)	28.1 (18.4)
Hardy et al. (2019)	Belgium (Cropland sites)	0–25	6.2 (6.3)	30.3 (13.9)		13.4 (1.1)	16.0 (10.6)
Kerré et al. (2016)	Belgium (Cropland sites)	0–23	6.2 (6.4)	35.0 (20.0)		22.2 (7.6)	16.0 (13.0)
Mastrolonardo et al. (2018)	Belgium (Forest sites)	0–20	3.5 (3.5)	161.7 (31.5)		113.9 (3.1)	51.6 (25.5)
Pollet et al. (2022)	Belgium (Forest sites)	0–10	3.7 (3.7)	103.0 (88.0)	6.4 (6.2)		7.73 (8.38) pot
Abdelrahmen et al. (2018)	Germany	0–5	4.9 (5.1)	144.0 (69.0)	5.7 (4.26)	39.9 (5.4)	
Buras et al. (2020)	Germany	n.a.	3.2 (3.6)	46.7 (11.0)	7.0 (0.4)		0.5–0.8 (0.5)
Heitkötter and Marschner (2015)	Germany	0–10	3.8 (3.9)	97.9 (65.9)	5.6 (5.4)		8.51 (6.9)
Hirsch et al. (2018b)	Germany	0–5	3.5 (3.6)	28.8 (10.9)	0.7 (0.1)		
Jabin et al. (2006)	Germany	0–10	4.4 (3.7)	284.0 (171.1)	8.7 (8.5)		
Carrari et al. (2016)	Italy	0–15	6.1 (5.9)	105.0 (56.5)	5.0 (4.2)		
Mastrolonardo et al. (2018)	Italy	0–22		119.5 (11.5)		47.4 (0.4)	
Lasota et al. (2022)	Poland			46.6 (21.9)	1.4 (1.3)		
Eriksson and Glav Lundin (2021)	Sweden	0–15	5.0 (4.7)				
Bonhage et al. (2020b)	USA	0–21	3.5 (4.1)				
Donovan et al. (2021)	USA	0–20	4.6 (4.9)	227.6 (154.6)	3.5 (3.3)		
Hart et al. (2008)	USA	0–5	4.9 (5.1)	61.6 (5.14)			14.7 (8.1).
Hirsch et al. (2018a)	USA	0–16	4.2 (3.7)	86.6 (71.1)	2.2 (6.0)		
Mikan and Abrams (1995)	USA	0–10		257.0 (132.0)			

shown that higher temporal variations in soil water contents further result from preferential flow of infiltrating water (Fig. 8a–d), which is affected by the pore size distribution and by seasonally varying hydrophobicity of the charcoal-rich substrate (Schneider et al., 2018). In addition to the temporal variations, strong preferential flow in RCH soils can also result in higher spatial variations in soil wetness along the profiles, especially for infiltration events after dry periods.

Another effect of the high porosity of the technogenic substrate is a reduction in soil thermal conductivity, logically associated with the high volumes of coarse, mainly air-filled pores. Soil temperature monitoring data (Fig. 9; Schneider et al., 2019) showed that this can have noticeable effects on the yearly soil temperature amplitudes both in the technogenic substrates and in underlying horizons, with increased temperature variations in the uppermost centimetres and lower variations in deeper parts of the RCH soil profiles.

However, results of soil moisture and temperature monitoring are not yet available for RCHs in many regions, and it is not yet clear if the effects observed for sandy soils in Brandenburg hold true in RCH landscapes with different geologic and climatic backgrounds. Furthermore, more detailed analyses of pore space are necessary to fully understand the effects of soil structure on biotic processes. The high variability of RCH effects on soil physical properties that is observed from studies in different regions can be related to differences in grain and pore size distributions of the unaffected soils and the mineral material in the RCH technogenic layers as well as to secondary effects such as modified soil aggregate and structure formation in the charcoal-rich substrates.

4.3. RCHs – chemical and mineralogical soil properties

Mikan and Abrams (1995) and Young et al. (1996), working in the North Central Appalachians of Pennsylvania, noted that hearth soils had unique soil chemistry patterns that could affect the chemistry of some woody plant species and even inhibit these species. Since then, several studies have focused specifically on the soil chemical properties of RCH soils (Table 3). The ubiquitously observed differences from reference soils are increases in total organic carbon (TOC), black carbon (BC) and exchangeable element concentrations. These differences are spatially distinct within hearths but are also detectable along gradients away from hearths (Donovan et al., 2021). The main controlling factor of these changes is the content of macro- and microscopic charcoal pieces that are intermixed with the mineral substrate, although there is evidence of increased non-pyrogenic SOC accumulation in RCH soils (Borchard et al., 2014; Heitkötter and Marschner, 2015; Kerré et al., 2016). Although a direct comparison between the studies listed in Table 3 is difficult based on their varying natural settings and sampling schemes, general trends regarding differences between RCH and reference soil chemistries can be derived. Overall, there is little change in soil acidity (pH), with an average difference of 0.11 (±0.38) pH units. TOC contents are on average 188 % (±280 %) higher, while in some cases, the difference can be up to approximately 1000 % (Hart et al., 2008; Mastrolonardo et al., 2018). The usual procedure in soil analysis to disregard soil particles >2 mm can result in underestimation of TOC contents in RCH soils, as large charcoal fragments will not be accounted for (Bonhage et al., 2020b; Mastrolonardo et al., 2018). When buried A horizons below the technogenic layers are preserved, they can show slightly reduced TOC contents compared with those of the A horizons of surrounding forest soils (Hirsch et al., 2018b). This reduction in SOM can be attributed to the ceased input of organic material along with proceeding mineralization of organic matter in the buried horizons and with the combustion of organic matter during hearth operation. The determination of BC concentrations is prone to methodological uncertainties, as different laboratory procedures usually target a different, more or less small, fraction of the black carbon continuum, and thus far, there has been no standard protocol established. On average, RCH soils have an increase in BC concentrations of approximately 3300 % (±3700 %). The increased charcoal/BC contents result in +37 % (±37 %) higher cation exchange capacities on average, caused by the negative surface charges of charcoal (Mastrolonardo et al., 2018), which can be increased by charcoal degradation processes, resulting in higher levels of surface hydroxyl functional groups (Hardy, 2017). Differences in available cation concentrations are discussed in the studies in detail, but notably, there are lower concentrations of available phosphorous reported in some RCH soils (e.g., Donovan et al., 2021; Hardy et al., 2016).

To date, information regarding soil mineralogical changes due to historical charcoal production is rare. Hirsch et al. (2018b) noted that the vertical heat flow of a burning RCH affects only the topmost centimetres of the buried horizons and that the layer immediately below the technogenic substrate is further influenced by thermally induced transformation of iron (hydr-)oxides, apparent in the reddish colour of the buried substrate (Fig. 8c, d). This heating influence on buried minerals enables RCH sites to be dated using the optical stimulated luminescence (OSL) technique (Karimi Moayed et al., 2020). Powell et al. (2012) and Dupin et al. (2019) discuss the increase in buried soil magnetic properties caused by hearth operation, which makes RCH sites potentially detectable by geophysical prospecting techniques.

5. RCHs – the ecological legacy

Sustainable ecological effects of charcoal in soils have been well reported for different biomes, with boreal forests in particular being studied (Pietikäinen et al., 2000; Wardle et al., 1998; Zackrisson et al., 1996). Likewise, significant inputs of charcoal into Chernozems and their effects on the biotic communities there have been described (Pinno and Bélanger, 2008). Furthermore, the properties of Terra Preta, a strongly anthropogenically influenced soil of the Amazon region, are determined by the input of charcoal (Glaser and Birk, 2012; Kim et al., 2007; Lucheta et al., 2017). While abundant research results are now available on the above-mentioned soils and ecosystems, the study of RCH soils is still very much in its initial stages.

5.1. Vegetation

Studies on the long-lasting ecological effects of RCHs on vegetation are still rare and partly reach different conclusions. However, there seem to be four main effects of RCHs on vegetation: 1) change in forest structure, 2) change in species composition, 3) change in recruitment pattern and ultimately 4) effects on productivity.

Change in forest structure:

The existence of charcoal burning with repeated cuttings and coppicing changes forest structures to more open canopies, facilitating light-demanding species such as oak over beech in temperate forests (Dupin et al., 2017; Máliš et al., 2020). Even after the abandonment of charcoal burning, the ecological legacies can linger for a long time. Trees can live for centuries, and long-term coppicing enhances the diversity of understorey vegetation (Máliš et al., 2020).

Change in species composition:

RCHs generally harbour increased species richness in the understorey in boreo-nemoral (Eriksson and Glav Lundin, 2021) as well as in Mediterranean forests (Carrari et al., 2017a). Even though tree species richness seems unaffected, at least in Tennessee (Hart et al., 2008), three different Mediterranean forest types showed decreased sapling richness in the regeneration layer (Carrari et al., 2017b). A decrease in (ericaceous) shrubs (Eriksson and Glav Lundin, 2021; Mikan and Abrams, 1995) and the existence of uncommon, more grassland-like, understorey species (Eriksson and Glav Lundin, 2021) underscore this shift in species composition, potentially driven by differences in soil chemistry between RCH and non-RCH sites.

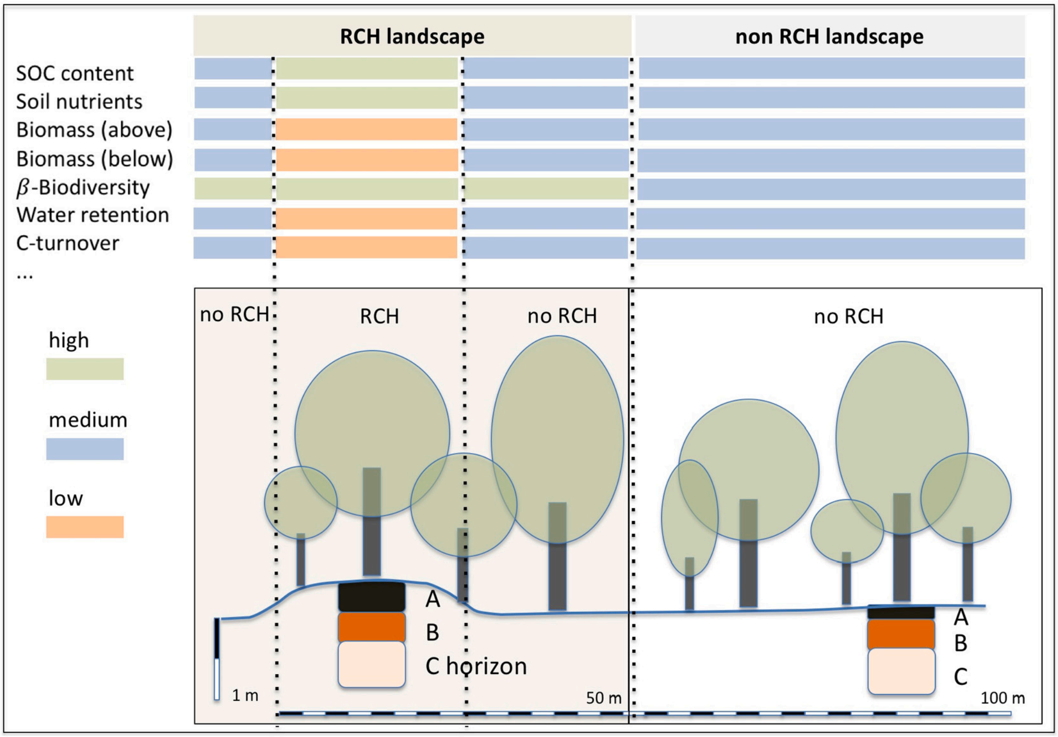

Fig. 10. Ecological differences between RCH and non-RCH landscapes.

Change in recruitment pattern:

Tree recruitment and forest regeneration seem to be difficult in RCHs, potentially because of soil chemical properties (Carrari et al., 2018; Mikan and Abrams, 1995). Even though tree seedlings grew taller on RCH soil, the germination success of beech and the survival of oak seedlings were negatively affected by the persistence of charcoal remains in the soil (Carrari et al., 2018), leading the authors to conclude that “charcoal platforms are a favorable microhabitat only in the first regeneration stages of woody species”.

Effects on productivity:

The productivity of trees on RCHs generally seems to be lower than that in non-RCH soils. While Hart et al. (2008) reported no difference in basal area between RCH and non-RHC sites in Pennsylvania, changes in soil physics, chemistry and nutrient availability seemed to negatively affect the stem growth of beech and silver birch in Belgium (Mastrolonardo et al., 2018) and Scots pine in eastern Germany (Buras et al., 2020). For the last two species, a higher drought sensitivity of trees at RCH sites was found, which may explain the observed differences in productivity (Al Jobayer et al., 2022). The potential higher fertility of RCH soils seems to affect wood chemistry (Buras et al., 2020) but leaf chemistry only marginally (Mastrolonardo et al., 2018).

5.2. Soil fauna

Even fewer studies have examined the soil fauna in RCHs (Jabin et al., 2006). A notable exception is the recent study by Pollet et al. (2022) focusing on Collembola as a dominant soil mesofauna group and the effects of centennial biochar on the taxonomic and functional diversity of communities in different land-use types. Land use (arable land, grassland and forest) affected Collembola communities considerably more than centennial charcoal. These results support previous findings for microbial communities at charcoal hearth sites in forests and arable fields, which were also primarily affected by different land uses (Hardy et al., 2019). Effects of RCH soil properties on fungal root growth have been suggested but have not yet been conclusively shown (Garcia-Barreda et al., 2017). Regarding modified decomposition and microbial activity, Kerré et al. (2017b) reported considerably lowered litter mineralization in historically charcoal-enriched soils.

6. Conclusion and outlook

RCH research has made marked progress in the last five years, and many previously unknown facts about RCH have been published. Until 10 years ago, RCH was hardly a topic in the fields of geomorphology, soil science or ecology, and archaeologists had shown only marginal interest in it. In particular, the availability of high-resolution LiDAR data has significantly advanced RCH research. The investigations of open-cast mining archaeology in Lower Lusatia, Germany, have also made very valuable contributions, as very accurate and unique documentation of >1500 RCHs has been carried out here over a period of >15 years (e.g., Lipsdorf, 2001; Raab et al., 2015; Rösler, 2008; Rösler et al., 2012). Thus, properties and features of the remains from historic charcoal burning, which are usually only indirectly accessible, could be compared and discussed with data from the excavations. In soil science, hearth remains have attracted attention in the community working on SOM, as RCHs can serve as comparative sites for studies on the ageing and degradation of biochar, which becomes even more important with respect to soil's potential for C sequestration, sustainable land use and climate change adaptation. This potential is certainly not yet exhausted.

Notably, despite the wide distribution of RCHs in many countries, some of their characteristics are similar. This concerns, above all, RCH types and RCH soils. As the similarities in RCH architecture between Europe and the USA show, the production methods were obviously largely the same, which can be explained by the immigration of charcoal burners from Europe to New England in pre-industrial times. In recent years, fundamental insights have been made in particular into the stratigraphy of RCHs and their soil properties. New regions have also been added to the mapping of hearths. In addition to manual surveying, new automated methods are being used more frequently. The morpho-genetic catalogue of Hirsch et al. (2020) is helpful for classified mapping, as it can be used to create a regionally standardized database for further investigations.

In comparison to the pedological and geomorphological knowledge that is now available on RCHs, hardly any related research has been carried out in the field of ecology. Only in recent years has there been increasing interest in this area. As we have seen in the few studies, the legacy effect of past charcoal burning is detectable in not only the abiotic but also the biotic status of ecosystems and thus should also affect the interactions between soils and organisms. However, we simply do not know very much about this effect. We thus should foster research activities that study these interdependencies, realizing that RCH landscapes have immanent properties controlled by a small landform mosaic (Fig. 10). Furthermore, interdisciplinary research should now elucidate interacting processes between the abiotic and biotic components. The main questions are (i) to what extent RCH-specific soil properties control biotic communities, (ii) whether species with preferences act as indicators, (iii) what the impacts of RCHs on the performance/fitness and functions of biotic communities are, (iv) whether there are differences in stress resistance and resilience of biotic communities between RCH and non-RCH sites, (v) whether biota-driven soil processes (e.g., decomposition and turnover rates) are affected by RCHs, and (vi) what the impact of RCHs on nutrient dynamics is (plant uptake, allocation in plants, microbial activity, etc.).

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thomas Raab reports financial support was provided by German Research Foundation.

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